AFRL-RX-TY-TR-2011-0098

UTILIZATION OF PHASE CHANGE MATERIALS (PCM) TO REDUCE ENERGY CONSUMPTION IN BUILDINGS

Ragab M. Moheisen, Keith A. Kozlowski, Aly H. Shaaban, Christian D. Rasmussen, Abdelfatah M. Yacout and Miriam V. Keith

Applied Research Associates
421 Oak Avenue
Panama City, FL 32401

Contract No. FA4819-09-C-0031

September 2011

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE

- **Air Force Materiel Command**
- **United States Air Force**
- **Tyndall Air Force Base, FL 32403-5323**

DISCLAIMER

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the 325th Fighter Wing Public Affairs Office at Tyndall Air Force Base, Florida and is available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

AFRL-RX-TY-TR-2011-0098 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

SALAVANI.REZA.1230156944 Digitally signed by SALAVANI.REZA.1230156944 DN: c=US, o=U.S. Government, ou=DoD, ou=PKI, ou=USAF, cn=SALAVANI.REZA.1230156944 Date: 2011.09.14 14:47:54 -05'00'

REZA SALAVANI
Work Unit Manager

RICHLIN.DEBRA.L.1034494149 Digitally signed by RICHLIN.DEBRA.L.1034494149 DN: c=US, o=U.S. Government, ou=DoD, ou=PKI, ou=USAF, cn=RICHLIN.DEBRA.L.1034494149 Date: 2011.11.03 13:11:55 -05'00'

DEBRA L. RICHLIN, DR-III
Acting Chief, Airbase Engineering Development Branch

PILSON.DONNA.L.1186939324 Digitally signed by PILSON.DONNA.L.1186939324 DN: c=US, o=U.S. Government, ou=DoD, ou=PKI, ou=USAF, cn=PILSON.DONNA.L.1186939324 Date: 2012.01.03 13:29:32 -06'00'

DONNA L. PILSON, LtCol, USAF
Deputy Chief, Airbase Technologies Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
14-SEP-2011

2. REPORT TYPE
Final Technical Report

3. DATES COVERED *(From - To)*
01-OCT-2009 -- 31-MAR-2011

4. TITLE AND SUBTITLE
Utilization of Phase Change Materials (PCM) to Reduce Energy Consumption in Buildings

5a. CONTRACT NUMBER
FA4819-09-C-0031

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
4915C19C

6. AUTHOR(S)
Moheisen, Ragab M.; Kozlowski, Keith A.; Shaaban, Aly H.; Rasmussen, Christian D.; Yacout, Adbelfatah M.; Keith, Miriam V.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Applied Research Associates
421 Oak Avenue
Panama City, FL 32401

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Materials and Manufacturing Directorate
Airbase Technologies Division
139 Barnes Drive, Suite 2
Tyndall Air Force Base, FL 32403-5323

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RXQES

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RX-TY-TR-2011-0098

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Ref Public Affairs Case # 88ABW-2012-0179, 10 January 2012. Document contains color images.

14. ABSTRACT
The purpose of this study was to determine the effectiveness of using Phase Change Materials (PCM) to achieve energy savings for the Air Force. This was accomplished through both analytical and experimental work. The experimental work included a variety of configurations representing installation of PCM in a typical wall construction as well as in a typical air handling plenum. These configurations were installed in a calorimetric room with a constant heat source. The temperature of the room was plotted versus time to determine the ability of the PCM to absorb the energy. The analytical work focused on developing analytical models of the heat transfer and phase transition characteristics of the material.

15. SUBJECT TERMS

phase change materials, PCM, heat transfer, phase transition, thermal mass

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	69	Reza Salavani
					19b. TELEPHONE NUMBER *(Include area code)*

Reset

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENT

The authors wish to acknowledge and thank the HQ Air Force Civil Engineer Support Agency and Mr. Quinn Hart for supporting and funding this effort.

1. EXECUTIVE SUMMARY

Phase-Change Materials (PCM) are a relatively new class of building materials that are used to increase the effective thermal mass of a structure. They are products designed to undergo a phase change from liquid to solid or vice versa near typical room temperature. Due to the relatively large energies involved in the phase change, PCM are able to store or release large quantities of heat per unit mass through these phase transitions. This is important to Air Force civil engineers because an increase in thermal mass reduces peak heating and cooling loads. This allows reduction in equipment capacity, provides peak shifting of electrical demand and, in some climates, greatly reduces the need for air conditioning by increasing the effectiveness of economizers.

HQ Air Force Civil Engineer Support Agency (AFCESA) is seeking design criteria for the use of PCM in standard Department of Defense (DoD) structures and heating, ventilation and air conditioning (HVAC) system applications to assess benefits of PCM in cutting energy demand. The Air Force Research Laboratory (AFRL), at the request of AFCESA, has investigated the feasibility of using PCM to help installations meet the energy reduction goal outlined in Executive Order 13423 and reduce facility life cycle costs.

The purpose of this study was to determine the effectiveness of using PCM to achieve energy savings for the Air Force. This was accomplished through both analytical and experimental work. The experimental work included a variety of configurations representing installation of PCM in a typical wall construction as well as in a typical air handling plenum. These configurations were installed in a calorimetric room with a constant heat source. The temperature of the room was plotted versus time to determine the ability of the PCM to absorb the energy.

The analytical work focused on developing models of the heat transfer and phase transition characteristics of the material. These models formed the basis for a computer code that was written to provide a simulation tool for evaluation of PCM.

Although this investigation was not exhaustive, the findings indicate that PCM-type products may enable energy savings, peak shifting and temperature leveling for many installations. Based on the results of the study, our recommendation is that architects and engineers consider the installation of PCM as a potential energy savings for future Air Force remodeling projects or new construction. The installed cost of PCM should be evaluated versus local utility rates and local climate conditions to perform a business-case evaluation to determine if PCM makes sense in a given project. To facilitate this evaluation, AFRL has prepared an Excel spreadsheet to help decision makers determine if PCM are right for their specific project.

2. INTRODUCTION

2.1. Background

Thermal energy can be stored as sensible heat, whereby the temperature of the storage material varies with the amount of energy stored, or as latent heat in which energy storage takes place when a substance changes from one condensed phase to another by either melting or freezing. PCM are a relatively new class of materials designed to store energy as latent heat. PCM are classified as organic materials such as paraffin waxes, inorganic materials such as salt hydrates, and eutectics, which are a mix of organic and inorganic PCM[1]. Among heat storage techniques, latent heat thermal energy storage is particularly attractive due to its ability to provide large energy storage density per unit mass and per unit volume, and its ability of storing heat at a constant temperature corresponding to the phase transition temperature characteristic of the PCM.

Builders and architects have long known that thermal mass, i.e., the ability to store thermal energy, contributes to improved energy performance of a structure. Historically, they have had to rely on large masses of concrete, brick or thick plaster walls to achieve these results. Since PCM relies on the comparatively large energies associated with material phase change, these same effects can now be achieved with stud/drywall types of construction.

Although available in various configurations, the work done by the AFRL focused on a product which had the PCM material contained in individual pouches, held together by a plastic packing sheet. These sheets were stapled onto typical 2 in × 6 in wooden studs and covered in drywall to simulate installation in a common wall. The wall also contained typical fiberglass insulation. Figure 1 shows PCM mats installed in a typical wall setup.

Figure 1. PCM Mats Installed in a Typical Wall

2.2. Literature Review

2.2.1. PCM and its Applications

A review of latent heat storage materials and their systems by Sharma *et al*[1] aimed at helping researchers in this area find a suitable PCM for various purposes, a suitable heat exchanger with ways to enhance the heat transfer, and a variety of designs to store the heat using PCM for diverse

applications, e.g., space heating and cooling, solar cooking, greenhouses, solar water heating and waste heat recovery systems. Techniques for measurement of thermophysical properties, studies on thermal cycles for long-term stability, corrosion of the PCM and enhancement of heat transfer in PCM were discussed. New PCM innovations were also included for awareness of new applications. The review contained a list of about 250 PCMs and more than 250 references.

Khudhair *et al*[2] suggested that energy storage in the walls, ceiling and floor of buildings may be enhanced by encapsulating a suitable PCM within these surfaces to capture solar energy directly and increase human comfort by decreasing the frequency of swings in internal air temperature and maintaining the temperature closer to the desired value for a longer period of time. Their paper summarized the investigation and analysis of thermal energy storage systems incorporating PCM for use in building applications. Ongoing research in thermal storage in which the PCM were encapsulated in concrete, gypsum wallboard, ceiling and floor was discussed. Also discussed were problems associated with the application of PCM—selection of materials and methods used to contain them.

2.2.2. Benefits of Applying PCM in Walls

Voelker *et al*[3] stated that overheating is a major problem in many modern buildings, due to the utilization of lightweight construction materials with low heat-storing capacity. A possible answer to this problem was the utilization of PCM to increase the thermal mass of a building. These materials change their state of aggregation within a defined temperature range. A useful PCM for buildings shows a phase transition from solid to liquid and back. The thermal mass of the materials is increased by the latent heat. A modified gypsum plaster and a salt mixture were chosen as two materials for a study of their capacity to buffer room temperature changes. For realistic investigations, test rooms were erected in which measurements were carried out under different conditions such as temporary air change, alternate internal heat gains or clouding. The experimental data were also reproduced by application of a mathematical model.

Ahmad *et al*[4] considered different types of wallboards containing PCM with an objective of defining passive components for the envelope of buildings. To lower the investment costs, the wallboards were made from commercial panels after a first attempt to use gypsum walls. Three types of wallboards were studied: (i) a polycarbonate panel filled with paraffin granulates; (ii) a polycarbonate panel filled with polyethylene glycol (PEG 600); (iii) a poly(vinyl chloride) (PVC) panel filled with PEG 600 and coupled to a vacuum insulation panel (VIP). An experimental set-up was built to determine the thermal response of these wallboards. Experimental results were compared to those obtained by a numerical simulation in which an apparent heat capacity method was used. The final results showed that the last studied wallboard, number iii, could be used in the test cells under construction to validate the concept.

Light envelopes are more and more frequently used in modern buildings but they do not provide sufficient thermal inertia. A solution to this is to incorporate PCM in buildings' envelopes. Ahmad *et al*[5] reported the performance of a test cell fabricated from light wallboards containing PCM, subjected to climatic variation, compared to a test cell built without PCM. To improve the wallboard efficiency a VIP was utilized with the PCM panel. This new structure allowed the apparent heat capacity of the building to be increased, the solar energy transmitted by windows to be stored without raising the indoor cell temperature, and the thickness of the wallboard to be

decreased compared with that of traditional wallboards. An experimental study was carried out by measuring temperatures of and heat fluxes through the wallboards, and the indoor temperature. A numerical simulation using TRNSYS software was carried out by adding a new module representing the new wallboard. It showed good agreement with experimental results. This new tool will allow users to simulate the thermal behavior of buildings having walls with PCM.

Kissock *et al*[6] summarized their experimental and simulated study of the thermal performance of phase-change wallboard (PCW) in simple structures. Two 1.22-m (4-ft) × 1.22-m (4-ft) × 0.61-m (2-ft) test cells were built using common light-frame construction practices. One wall of each test cell was a transparent acrylic sheet, to allow solar radiation to penetrate the cell. The cells were oriented so that the glazing faced south. Conventional wallboard was installed in the control test cell, and wallboard imbibed with 28% by weight K18 PCM was installed in the second test cell. A differential scanning calorimeter was used to measure the effective heat capacities of both the PCW and conventional wallboard. Solar radiation, ambient temperature and interior temperatures in the test cells were continuously monitored from 10/28/97 to 11/10/97. Results indicated that peak temperatures in the phase-change test cell were up to 18 °F (10 °C) lower than in the control test cell during sunny days. A modified finite-difference simulation model was able to predict interior wall temperatures in the test cells with reasonable accuracy (average error < 3 °F (1.7 °C)) based on measured property and environmental data.

A new PCM wallboard was experimentally investigated by Kuznik *et al*[7] to enhance the thermal behavior of a lightweight building internal partition wall. The experiments were carried out in a full-scale test room that was completely controlled. The external temperature and radiative flux dynamically simulated a summer day repetitively. The differential test was applied to walls with and without PCM material under the same conditions. The PCM reduced the room air temperature fluctuations, in particular when overheating occurred. A numerical model has been used to investigate energy storage. Five millimeters of PCM wallboard doubled the energy storage during the experiment. The experiments were fully described so that the results can be used for the validation of numerical models dealing with PCM.

Neeper[8] examined the thermal dynamics of PCM wallboard subjected to a diurnal variation of room temperature, but not directly illuminated by the sun. The purpose of his work was to provide guidelines useful in the selection of an optimal PCM and in estimating the benefits of PCM architectural products. The amount of energy stored during a daily cycle depends upon the melt temperature of the PCM, the temperature range over which melting occurs, and the latent capacity per unit area of wallboard. Situations placing the wallboard on an interior partition or on the inside of the building envelope were investigated separately. It was determined that, in most cases, the maximum diurnal energy storage occurred when the PCM's melt temperature was close to the average room temperature. Diurnal energy storage decreased if the phase transition occurred over a range of temperatures. The diurnal storage achieved in practice may be limited to the range 300–400 kJ/m^2, even if the wallboard has a greater latent capacity. The implications of these findings for test room experiments were discussed.

Integration of PCM into building fabrics is considered to be one potential way of minimizing energy consumption and CO_2 emissions in the building sector. To assess the thermal effectiveness of this concept, Darkwa *et al*[9] evaluated composite PCM drywall samples, i.e.,

randomly mixed and laminated PCM drywalls, in a model passive solar building. For a broader assessment, effects of three phase change zones (narrow, intermediate and wide) of the PCM sample were considered. The results showed that the laminated PCM sample with a narrow phase change zone was capable of increasing the minimum room temperature by about 17% more than the randomly mixed type. Even though there was some display of non-isothermal phase change processes, the laminated system proved to be thermally more effective in terms of evolution and utilization of latent heat. Further heat transfer enhancement is required for the development of the laminated system.

2.2.3. Implementing PCM in Ceilings/roofs

Koschenz *et al*[10] described the development of a thermally activated ceiling panel for incorporation in lightweight and retrofitted buildings. The system allowed the use of renewable energy sources to heat and cool office and industrial buildings. The design for the new ceiling panel exploited the properties of paraffin as a PCM. Its high thermal storage capacity during phase change, up to 300 Wh/m^2, enabled the overall panel thickness to be limited to 5 cm. Active control of thermal storage was achieved by means of an integrated water capillary tube system. Their research included development of a numerical model for computation of the thermal behavior of wall and ceiling systems incorporating PCM. They performed simulation calculations to determine the necessary thermal properties of the ceiling panels and specify requirements for the materials to be used. Laboratory tests were performed to verify the system's performance.

In their analysis on the thermal performance of a building roof incorporating PCM for thermal management, Pasupathy *et al*[11] stated that thermal storage plays a major role in a wide variety of industrial, commercial and residential applications when there is a mismatch between the supply and demand of energy. The authors indicated that latent heat storage in PCM is attractive because of its high energy storage density and its isothermal behavior during the phase change process. Also noted were several promising developments taking place in the field of thermal storage using PCM in buildings. "It has been demonstrated that, for the development of a latent heat storage system (LHTS) in a building fabric, the choice of the PCM plays an important role in addition to heat transfer mechanism in the PCM. Increasing the thermal storage capacity of a building can enhance comfort and decrease the frequency of perceptible internal air temperature swings by holding the indoor air temperature closer to the desired temperature and for a longer period of time."[11] A study of the thermal performance of an inorganic eutectic PCM-based thermal storage system for thermal management in a residential building included experimental measure-ments and a theoretical analysis. Experiments were also conducted by circulating water through tubes kept inside the PCM panel to test its suitability for the summer months. To achieve the optimum design for the selected location, several simulation runs were made using average ambient conditions for all the months in a year and for various other parameters of interest.

2.2.4. Incorporating PCM in Floors

Nagano *et al*[12] proposed a new floor supply air conditioning system, using PCM to augment thermal storage. A scale model was constructed. Granules containing PCM with a phase change temperature of about 20 °C were made from foamed glass beads and paraffin waxes. Results from measurements simulating an air conditioning schedule in office buildings indicated that 89% of the daily cooling load could be stored each night in a system that used a 30-mm-thick packed bed of the granular PCM.

A duct system of laminated, phase-change concrete has been numerically analyzed for cooling applications in buildings by Darkwa[13]. The analysis showed that the number of transfer units (NTUs) has considerable effect on the thermal performance of the system. For instance, the highest factor of PCM melting thickness and surface temperature fraction were achieved with the lowest NTU value, 0.1. In terms of cooling effects, the two scenarios of the simulation achieved maximum cooling capacities of 12.5 kW and 25 kW, respectively. To achieve effective thermal response in a mechanically ventilated ductwork system, some form of turbulent flow through surface roughness and configuration would have to be created. Even though the model was developed based on the assumption that each PCM is pure and will melt at a specific temperature, the results appeared to be a fair representation of what might happen in practice. Experimental validation is recommended as a step toward commercial and economic evaluation.

2.2.5. Implementing PCM in the Building Envelope

As quoted by Zhang *et al*[14], latent heat thermal energy storage (LHTES) is becoming more and more attractive for space heating and cooling of buildings. Incorporation of LHTES in buildings has the following advantages: (1) it narrows the gap between the peak and off-peak loads of electricity demand; (2) it lowers operating expenses by shifting electrical consumption from peak periods to off-peak periods—the cost of electricity at night is often less than during the day; (3) particularly for space heating in winter, it utilizes solar energy continuously by storing it during the day and releasing it at night, thus reducing diurnal temperature fluctuation, which improves thermal comfort; (4) it can store natural cooling by ventilation at night, especially in the summer, and release it during the day to lower the room temperature, thus reducing the cooling load of air conditioning. Their paper investigated previous work on thermal energy storage by incorporating PCM in the building envelope. The basic principle, candidate PCMs and their thermophysical properties, incorporation methods, thermal analysis of the use of PCM in walls, floor, ceiling and window etc. and heat transfer enhancement were discussed. It was shown that with appropriate PCM selection and a suitable incorporation method in building material, LHTES can be economically efficient for heating and cooling of buildings. However, several problems were noted that must be addressed before LHTES can reliably and practically be applied.

At Oak Ridge National Laboratory (ORNL), Kosny *et al*[15] summarized the results of an experimental and theoretical analysis performed at ORNL during 2003–2006 on organic PCM used in building thermal envelopes. PCM have been studied and tested as a thermal mass component in buildings for at least 40 years; most studies have found PCM enhances building energy performance. However, problems such as high initial cost, loss of phase-change capability, corrosion, and PCM leakage have hampered widespread adoption. Paraffinic hydrocarbon PCM generally performed well, but increased the flammability of the building envelope. Traditionally, PCM have been used to stabilize interior building temperatures. Thus, the best locations for PCM were interior building surfaces—walls, ceilings, or floors. In research underway at ORNL, PCM were used as an integral part of the building thermal envelope. Microencapsulated paraffinic PCM were positioned in the wall cavity or installed as a part of the attic insulation system.

Muruganantham *et al*[16] stated that PCM play an important role as a thermal energy storage device by utilizing their high storage density and latent heat property. One of the potential applications of PCM in buildings is by incorporating them in the building envelope for energy conservation. During the summer cooling season, the main benefits are a decrease in overall

energy consumption by the air conditioning unit and the time shift in peak load during the day. Experimental work was carried out by Arizona Public Service (APS) in collaboration with Phase Change Energy Solutions (PCES) Inc. with a new class of organic-based PCM. The experimental setup showed maximum energy savings of about 30%, a maximum peak load shift of about 60 minutes and maximum cost savings of about 30%.

Ismail *et al* [17] presented the results of a numerical and experimental study of PCM-filled walls and roofs under real operational conditions to achieve passive thermal comfort. The numerical part of the study was based on a one-dimensional model for the phase change, controlled by pure conduction. Real radiation data were used to determine the external face temperature. The numerical treatment used finite difference approximations and the alternating direction implicit method. The results obtained were compared with field measurements. The experimental setup consisted of a small room with a movable roof and a side wall. The roof was constructed using traditional methods but with the PCM enclosed and thermocouples distributed across its cross section. Another roof constructed without the PCM, but otherwise identical, was also used during comparative tests. The movable wall was also constructed traditionally except that the PCM was enclosed. Again, thermocouples were distributed across the wall thickness to enable measurement of local temperatures. Another wall, identical except for the PCM, was used during comparative tests. The PCM used in the numerical and experimental tests comprised a mixture of two commercial grades of glycol that gave the desired fusion temperature range. Comparison of the simulation results with experimental data indicated good agreement. Field tests also indicated that the PCM used was adequate and the concept was effective in maintaining the indoor temperature very close to the prescribed comfort limits. Further economic analysis indicated that the concept could effectively help to reduce electric energy consumption and improve the energy demand pattern.

2.2.6. Modeling Peak Load Shifting due to PCM

Halford *et al*[18] address potential peak air conditioning load shifting strategies using encapsulated PCM. The materials considered were designed to be installed within ceiling or wall insulation to delay peak air conditioning demand times. To assist in understanding the behavior of this material, an idealized model was developed that uses the one-dimensional diffusion equation driven by time-varying temperature functions imposed at the boundaries. In developing the model, the phase-change temperature and latent heat of melting were critical variables that were treated parametrically. Other variables, such as the characteristic ambient temperature variations and the thermostat set point, were varied relative to the phase-change temperature. Comparisons were made to time-dependent variations of heat flow with and without PCM.

Halford *et al*[19] stated that peak demand for electricity in many parts of the country, particularly the desert Southwest, is of critical concern to utilities. For locations with high air conditioning demand, an approach to shift peak demand is to use PCM in the ceiling, which melts during peak demand periods and then is refrozen at off peak times. The purpose of their work was the development of a numerical model to evaluate the load shifting abilities of this type of approach. The simulation was based upon the solution to the one-dimensional diffusion equation driven by a sinusoidally varying ambient temperature imposed on the outer surface. In developing the model, the PCM was taken as a horizontal layer within the insulation. Its location and mass were treated as parameters. Other variables, such as the characteristic ambient temperature variations and the

thermostat set point, were varied relative to the phase-change temperature. The output of the model was the time-varying heat flux at the inner surface over the period of a day. Their simulation was intended as a first approximation to model an extremely complex heat transfer problem. Many simplifying assumptions were made that have yet to be validated, and at that publication the model had not been compared to any experimental results. Early results did, however, show some general trends. For all cases simulated, total melting and refreezing of the material never exceeded 20% of the total mass of material. This indicated either the need for a more effective means of refreezing the material during off-peak times or a smaller mass of material. Although mass utilization was relatively low, the study showed that even when only a small fraction of the mass was being used, a considerable load shift was theoretically possible.

2.2.7. Mathematical Modeling of PCM Used in Latent Heat Thermal Energy Storage Systems

The major methods of mathematical modeling of solidification and melting problems were reviewed by Hu *et al*[20]. They presented different analytical methods, which are used as standard references to validate numerical models. Various mathematical formulations to numerically solve solidification and melting problems were categorized. Relative merits and disadvantages of each formulation were analyzed. Recent advances in modeling solidification and melting problems associated with convective motion of the liquid phase were discussed. Based on this comprehensive survey, guidelines were developed to choose a correct mathematical formulation for solving solidification and melting problems.

Verma *et al*[21] used mathematical modeling of an LHTES to optimize material selection and systems design. In their paper, two types of models were mainly discussed, those based on the first law of thermodynamics and those based on the second law of thermodynamics. The important characteristics of different models and their assumptions were presented and discussed. Experimental validation of some models was also presented.

2.2.8. Numerical Simulation of PCM in Building Applications

Rabin *et al*[22] presented a simple, efficient numerical technique for solving transient multidimensional heat transfer problems with melting/solidification processes. They proposed a technique comprising an enthalpy-based method to solve the problems by a finite difference scheme with an assumption of lumped system behavior for each node. The computational technique was able to consider a variety of boundary conditions, i.e., conduction, convection and radiation alone or in combination. The numerical method neglected convection effects in the liquid phase. The importance of this method lies in the fact that solutions were obtained with a personal microcomputer, thus providing a convenient and reliable tool for wide use in solving many problems of practical interest. The proposed method was verified against two exact solutions available from literature for a one-dimensional semi-infinite domain, the first with a constant temperature boundary condition and the second with constant heat flux. The technique was demonstrated by solving four different cases of two-dimensional problems. The results obtained utilizing the technique presented in their paper showed good agreement when compared with numerical results from the reviewed literature using finite difference and finite element methods.

An interesting possibility in building application is the impregnation of PCM into porous construction materials, such as plasterboard or concrete, to increase its thermal mass. The

thermal improvements in a building due to this type of inclusion of PCM depend on the climate, design and orientation of the construction, and the amount and type of PCM. Therefore, these projects require a complete simulation of the thermal behavior of the designed space in the conditions of use. Using the program Ibaneza *et al*[23], presented a simple methodology for energetic simulation of buildings including elements with PCM TRNSYS, and validated their results. Their procedure did not aim at simulating real transfer processes inside the materials with PCM, but instead at evaluating the influence of PCM in walls/ceiling/floor on the whole energy balance of a building. The key parameter in the simulations was the equivalent heat transfer coefficient, which has to be determined for each material. Experimental evaluation of the coefficient was presented.

Heim *et al*[24] utilized the software package ESP-r to model the behavior of PCM using ESP-r's special materials facility. The effect of phase transition was added to the energy balance equation as a latent heat generation term according to the effective heat capacity method. Numerical simulations were conducted for a multi-zone, highly glazed and naturally ventilated passive solar building. PCM-impregnated gypsum plasterboard was used as an internal room lining. The air, surface and resultant temperatures were compared with the no-PCM case and the diurnal latent heat storage effect was analyzed. While this effect did not cause a considerable reduction in the diurnal temperature fluctuation, the PCM did effectively store solar energy in the transition periods. Additionally, the energy requirement at the beginning and end of the heating season was estimated and compared with ordinary gypsum wallboard. Within this comparison, the PCM composite solidification temperature was 22 °C (i.e. 2 K higher than the heating set-point for the room). The results showed that solar energy stored in the PCM–gypsum panels can reduce the heating energy demand by up to 90% at times during the heating season.

Kuznik *et al*[25] stated that the use of PCM in construction allows the storage/release of energy from the solar radiation and/or internal loads. Therefore, the application of such materials for lightweight construction (e.g., a wood frame house) makes it possible to improve thermal comfort and reduce energy consumption. A wallboard composed of a new PCM material was investigated to enhance the thermal behavior of a lightweight internal partition wall. Their work was focused on the optimization of PCM's thickness. The in-house software CODYMUR was used to optimize the PCM wallboard by the means of numerical simulations. The results showed that an optimal PCM thickness exists. The optimal PCM thickness value was then calculated for use in construction.

Kendrick *et al* [26] reviewed methods to incorporate PCM in building materials, particularly in passive applications. A simulation study using IES Virtual Environment package Apache was carried out on PCM-impregnated plasterboard, investigating various fusion temperatures of the PCM during night, day and week-long tests in hot weather conditions. Different ventilation rates and varying conductivity values of the gypsum in the plasterboard were tested. It was shown that use of PCM offers significant advantages for both commercial and residential building applications, provided sufficient night ventilation is allowed.

3. APPROACH/METHODOLOGY

To investigate the feasibility of using PCM to meet energy and cost reduction objectives, a PCM was evaluated in a standard frame construction wall and in an air handling plenum. Three types of wall test were performed. The first test focused on the comparison and analysis of a sectional wall constructed with a different amount or thermal density of PCM in individual cavities. This test will be referred to as "comparison wall." The primary purpose of the comparison wall test was to provide a reference set of data for the analytical model. The second wall test was performed with the wall having the 2.0-lb/ft^2 PCM in the entire wall, which will be referred to as "2.0-lb/ft^2 wall." The third test was the control experiment performed on a wall without PCM.

Three types of plenum tests were also performed. The plenum was tested with no PCM, and with PCM densities of 0.56 lb/ft^2 and 2.0 lb/ft^2. For the plenum testing, our observation was that the differences among test runs were less than the inherent variability of the testing. Therefore, we were not able to draw conclusions for this application. It is our belief that the cause for the lack of difference in the various tests was insufficient PCM mass compared to the amount of airflow, aggravated by relatively poor heat transfer between air and the PCM. As a result, discussion of the plenum testing and results is limited.

Experimental measurements and testing were carried out in a controlled, calorimetric, environmental chamber at the Air Force Research Laboratory (AFRL/RXQES) facility located at Tyndall AFB, FL. A floor plan schematic of the chamber is shown in Figure 2. Performing the testing in this chamber allowed us to monitor and control experimental and environmental conditions and parameters as well as to mitigate outside influences that would affect test results.

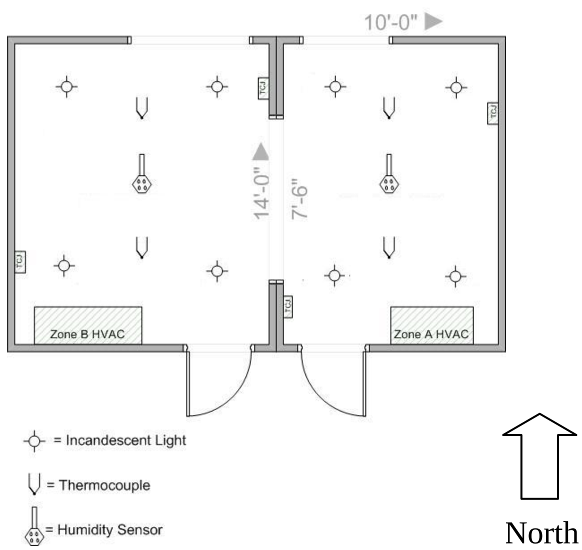


Figure 2. Calorimetric Environmental Chamber

The PCM chosen for this study was Thermester 23B BioPCM encapsulated mats, developed and supplied by Phase Change Energy Solutions, Inc. Testing was performed on two different densities per unit area: 0.56 lb/ft^2, shown in Figure 3, and 2.0 lb/ft^2, shown in Figure 4. PCM properties are highlighted in Table 1.

Figure 3. 0.56-lb/ft^2 PCM Mat

Figure 4. 2.0-lb/ft^2 PCM Mat

Table 1. PCM Properties

Description	PCM
Density (kg/m^3)	830
Melting Temperature (°C)	23
Specific Heat (kJ/kg·K)	2.1
Latent Heat (J/g)	200
Viscosity (cP @ 30 °C)	13
Boiling Point (°C)	260
Thermal Conductivity (W/m·K)	0.2

3.1. Wall Test

A 72-in × 90-in nominal wood-framed wall using 2-in × 6-in studs on 16-in centers with four independent testing cavities was utilized to investigate the energy effectiveness of PCM incorporated into a wall construction; the results were also used to develop the simulation model. The wall was constructed in the controlled calorimetric environmental chamber in the wall opening between Rooms A and B (shown as Zones A and B in Fig. 2). The overall construction of the nominal wall is depicted in Figure 5.

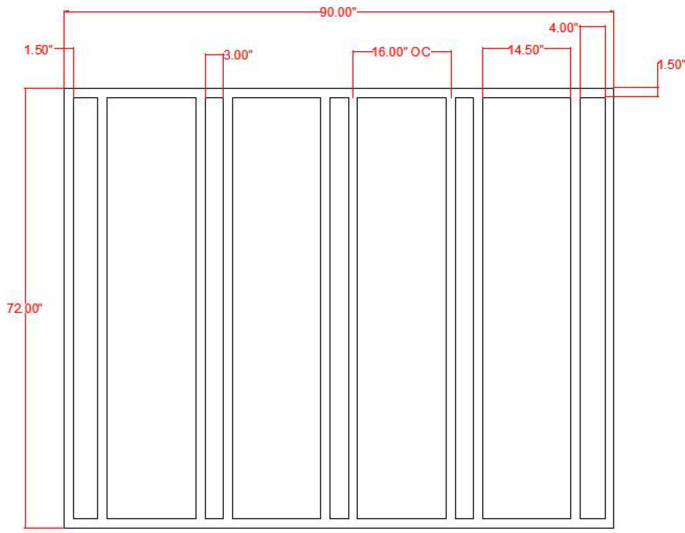


Figure 5. Nominal Wall Construction Schematic

3.1.1. Comparison Wall Test Setup

To investigate the thermal benefit and heat transfer characteristics of PCM, 0.56-lb/ft^2 and 2.0-lb/ft^2 PCM densities were retrofitted into individual test cavities in a nominal wall test setup. The test wall also featured one "standard" section, which did not include PCM, and one section that included 0.56-lb/ft^2 PCM, but no wallboard (reference Table 2). Surface temperatures of each layer were monitored and analyzed against maintaining a comfort level temperature range of 74–78 °F under various sensible heat loads.

From left to right in Room A, the four independent testing cavities were designated Sections 1 through 4. Each independent cavity was tested in the material layer configuration shown in Table 2; an overall schematic diagram is shown in Figure 6. All instrumentation used for sectional analysis was installed according to layer references shown in Table 3.

Table 2. Comparison Wall Test Cavity Layer Configuration

Section 1	Section 2	Section 3	Section 4
Room A			
	5/8-in Gypsum Wallboard		
0.56-lb/ft^2 PCM Mat		0.56-lb/ft^2 PCM Mat	2.0-lb/ft^2 PCM Mat
R19 Fiberglass Insulation			
R30 EPE Foam Insulation			
1/8-in Plywood			
Room B			

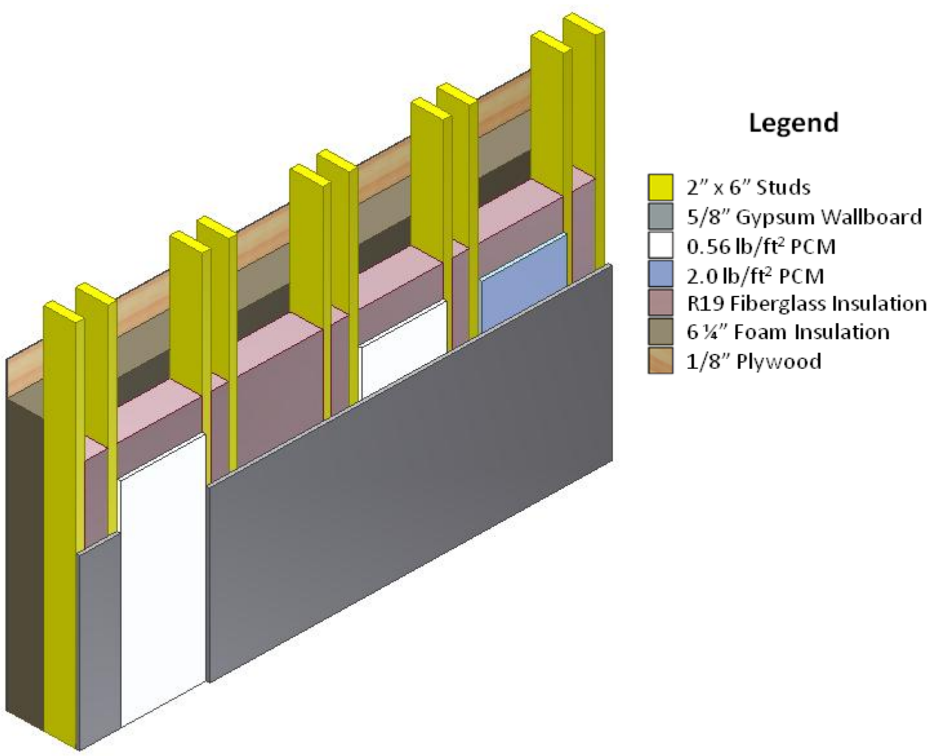


Figure 6. Schematic Diagram of Comparison Wall Test Setup

Table 3. Comparison Wall Instrumentation Layer Reference

Layer	Reference
1	Front side of 5/8-in wallboard surface exposed to Room A
2	Front side of PCM mat surface exposed to back side of 5/8-in wallboard
3	Front side of R19 fiberglass insulation surface exposed to backside of PCM mat
4	Back side of R19 fiberglass insulation exposed to 1/8-in plywood and Room B

Test cavity surface temperatures of each layer and section were recorded with Omega Precision Fine Wire Thermocouples (Part #: SA1-K-72) and monitored through National Instrument's LabView. Figure 7 shows an overall thermocouple sensor placement map for each layer (total of 10 sensors per layer). A grid location for each sensor was identified to guarantee similar placement of the sensors in all the layers within the wall cavity and across the wall sections. In addition, thermocouple sensors were placed in the center of calorimetric environmental chamber Room A and along the north, south and east walls for room monitoring and data analysis.

The comparison wall test matrix developed for the comparison wall test is shown in Table 4.

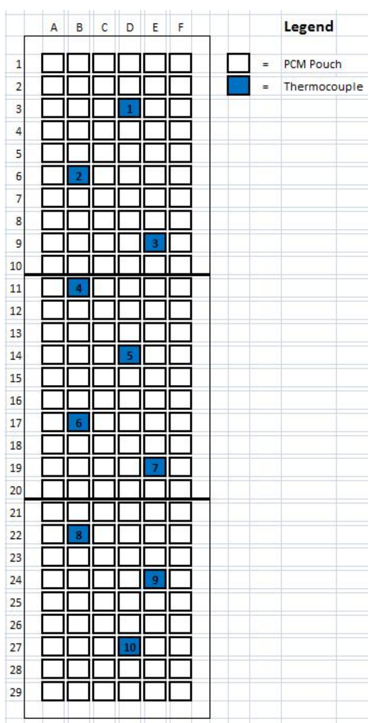


Figure 7. Comparison Wall Thermocouple Sensor Placement

Table 4. Comparison Wall Test Matrix

Run Order	Initial Room Temperature (°F)	Thermal Load (W)
1	78	400
2	78	100
3	76	100
4	78	400
5	78	250
6	74	100
7	74	400
8	76	400
9	76	100
10	74	250
11	76	250
12	78	100
13	74	100
14	76	400
15	74	400

3.1.2. Comparison Wall Test Procedure

To ensure all PCM mats were completely in a solid phase at the start of testing, the calorimetric environmental chamber was set at 68 °F in both Room A and Room B and allowed to reach steady-state conditions. PCM surface temperatures were monitored until Layer 2 and Layer 3 in each test cavity reached the solidification temperature of 73 °F, ensuring solid-phase uniformity.

Once uniformity was achieved, the room temperature of Room A was raised to the initial room temperature specified in the center column of the test matrix (Table 4).

As soon as the initial room temperature was reached, a thermal load was introduced to Room A via an alterable 20-amp load bank to simulate exposure of the wall to various heat loads. The load bank was set according to the test matrix as shown in Table 4 and turned on. LabView was used to record and monitor surface temperatures of Layers 1 through 4 of Sections 1 through 4. Room temperatures and condition parameters were also monitored and recorded for analysis. Completion of testing was attained once the room temperature increased and layer temperatures for each test cavity were uniformly above the melting temperature of the PCM. Load bank and calorimetric environmental chamber conditions were reset to their initial state conditions. The highlighted procedures were repeated for each sequential run order in the test matrix as shown in Table 4.

3.1.3. 2.0-lb/ft^2 Wall Test Set-up

To investigate the feasibility of peak shifting of energy demand to meet energy and cost reduction objectives, 2.0-lb/ft^2 PCM was retrofitted into each individual test cavity in a nominal wall test setup. Surface temperatures for each layer were monitored and analyzed for a comfort level temperature range of 74–78 °F under various sensible heat loads and compared to a baseline nominal wall (without PCM) installation under similar conditions.

Similar to the comparison wall test, from observation of the nominal wall from left to right in Room A, the four independent testing cavities were designated Sections 1 through 4 for reference and comparison analysis. Each independent cavity was tested with the material layer configuration shown in Table 5. An overall schematic diagram is shown in Figure 8. All instrumentation used for wall layers/sections was installed according to layer references similar to the comparison wall test, as shown in Table 3.

Table 5. 2.0-lb/ft^2 Wall Test Layer Configuration

Section 1	Section 2	Section 3	Section 4
Room A			
5/8-in Gypsum Wallboard			
2.0-lb/ft^2 PCM Mat			
R19 Fiberglass Insulation			
R30 EPE Foam Insulation			
1/8-in Plywood			
Room B			

Surface temperatures of each layer and test cavity section were recorded with Omega Precision Fine Wire Thermocouples (Part #: SA1-K-72) and monitored through LabView. Thermocouple sensor placement in accordance to Figure 9 for each test cavity was used. Similar to the comparison wall test setup, thermocouple sensors were placed in the center of calorimetric environmental chamber Room A and along the north, south and east walls for room monitoring and data analysis.

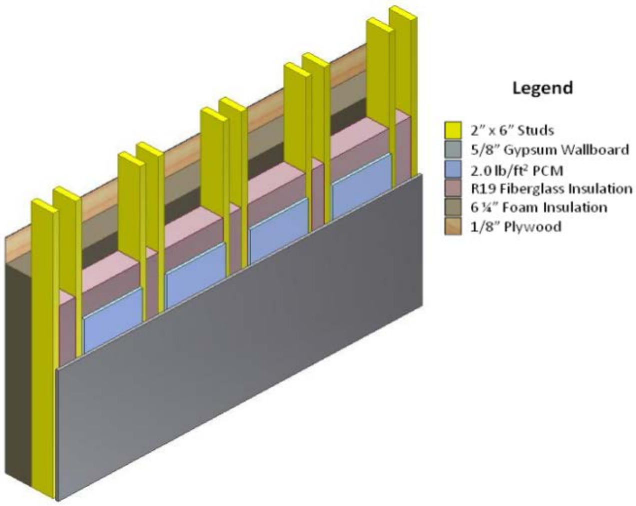


Figure 8. Schematic Diagram of 2.0-lb/ft^2 Wall Test Setup

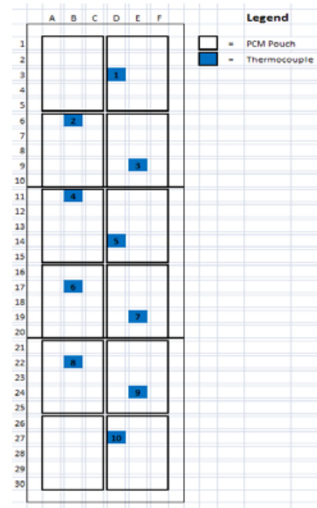


Figure 9. 2.0-lb/ft^2 Wall Thermocouple Sensor Placement

The matrix for testing and analysis of the 2.0-lb/ft^2 wall is shown in Table 6.

Table 6. 2.0-lb/ft^2 Wall Test Matrix

Run Order	Thermal Load (W)
1	100
2	250
3	400

3.1.4. 2.0-lb/ft^2 Wall Test Procedure

As in the comparison wall test, the calorimetric environmental chamber was set and soaked (kept at constant temperature for 12 to 18 hours) at 68 °F in Rooms A and B until they reached steady-state conditions. PCM surface temperatures were monitored until Layers 2 and 3 in each test cavity reached the solidification temperature, 73 °F, ensuring solid-phase uniformity. Once phase uniformity was achieved, a thermal load was introduced to Room A through an alterable 20-A load bank that was adjusted and turned on according to the run order of the test matrix. The thermal load ramped room, layer and section temperatures until PCM layer temperatures were above the melting temperature for the PCM mats. LabView recorded and monitored surface temperatures of Layers 1 through 4 of Sections 1 through 4. Room temperatures and condition parameters were also monitored and recorded for analysis. At the completion of the test, the load bank and calorimetric environmental chamber conditions were reset to their initial conditions. The highlighted procedure was repeated for each sequential run order in the test matrix.

A baseline test was also established for comparison. The 2.0-lb/ft^2 PCM mats and Layer 2 instrumentation were removed from the nominal wall test setup. The environmental chamber was set and soaked at 68 °F in Rooms A and B and allowed to reach steady-state conditions. A thermal load was introduced to Room A through an alterable 20-A load bank for latent and sensible heat

simulation. The load bank was adjusted and turned on according to the run order of a test matrix identical to the 2.0-lb/ft^2 PCM wall testing. The thermal load was allowed to ramp room, layer and section temperatures until relative layer and section uniformity was achieved. LabView was again used to record and monitor surface temperatures of Layers 1 through 4 of Sections 1 through 4. Room temperatures and condition parameters were also monitored and recorded for analysis. After test completion, the load bank and chamber conditions were reset to their initial conditions. The procedure was duplicated for each sequential run order in the test matrix.

3.2. Plenum Test

In this study, a 20-ft length wood framed plenum using 2-in × 6-in studs on 16-in centers with 15 independent cavities was constructed and utilized for analyzing the energy effectiveness of PCM incorporated into an HVAC air return distribution system. The plenum was constructed and assembled in the controlled calorimetric environmental chamber Rooms A and B and fitted through an insulated wall partition along the adjoining wall of the two rooms. The overall construction of the plenum is depicted in Figures 10–12.

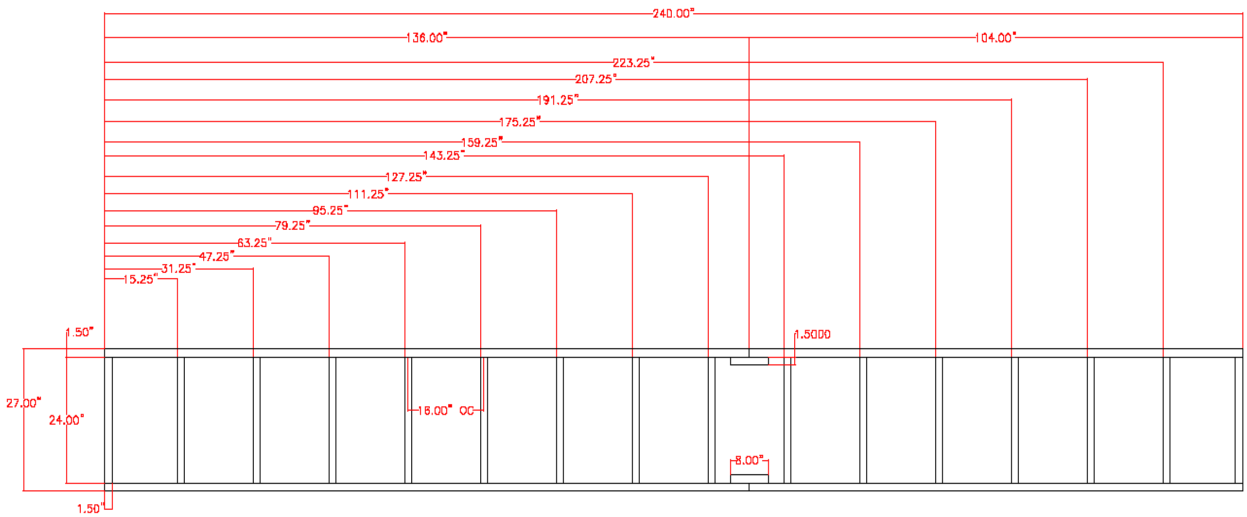


Figure 10. Plenum Construction Schematic Frontal View

Nominal R19 fiberglass insulation was used to fully insulate the interior cavities of the plenum. PCM-encapsulated mats with 0.56-lb/ft^2 and 2.0-lb/ft^2 densities were installed along the interior bottom of the plenum starting with the third test cavity and tested sequentially after a baseline was established. The plenum was sealed on the sides, ends and top using ½-in oriented strand board (OSB). For simulation of an installation ceiling, the plenum bottom was sealed using 5/8-in gypsum wallboard with a fitted 24-in × 24-in air return grille at the end of the plenum in Room A. Stands were also constructed to suspend the plenum to a desired testing height. A cut-away schematic of the plenum is shown in Figure 13.

Surface temperatures of each layer were recorded with Omega Precision Fine Wire Thermocouples (Part #: SA1-K-72) and monitored with LabView. Airflow across the plenum was also monitored and recorded through LabView software. Three air velocity transmitters supplied by E&E Elektronik (Part #: EE65), Figure 14, were utilized and installed. All air

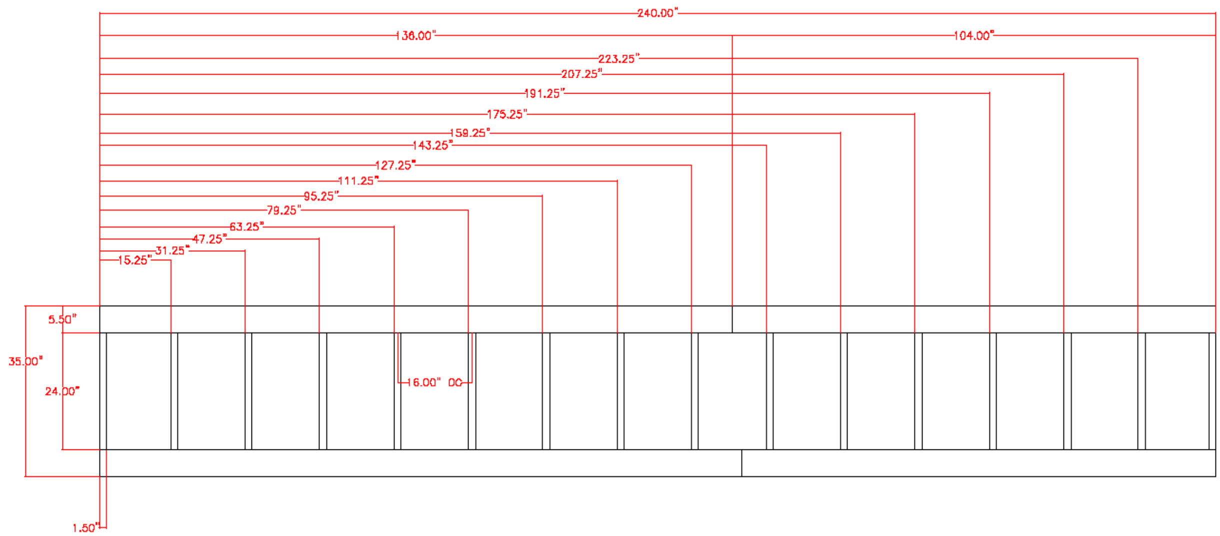


Figure 11. Plenum Construction Schematic Side View

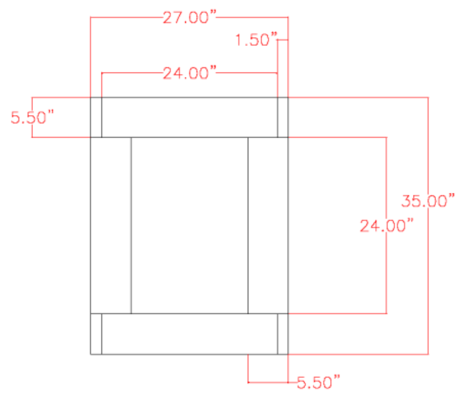


Figure 12. Plenum Construction Schematic End View

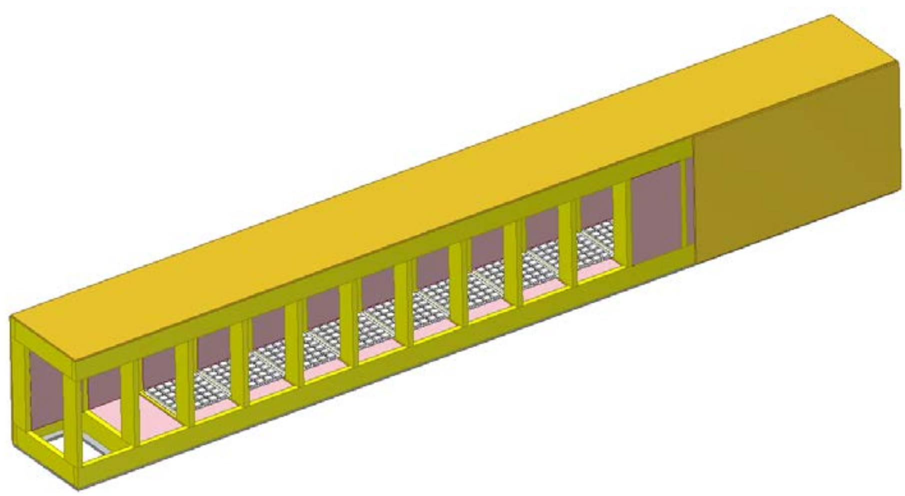


Figure 13. Cut-Away Schematic of Air Plenum

Distribution A: Approved for public release; distribution unlimited. 88ABW-2012-0179, 10 January 2012

velocity transmitter probes were installed according to manufacturer instructions with the probe centered in the plenum. To create the desired air flow expressed in cubic feet per minute (CFM) across the plenum, an alterable high air velocity ventilator supplied by Americ Corporation (Part #: VAF-3000), Figure 15, was used and installed at the end of the plenum in Room B.

Figure 14. Air Velocity Transmitter

Figure 15. High-Velocity Ventilator

Thermocouple and air velocity sensor placement in accordance to Figures 16 and 17 was used across each testing layer. All instrumentation used for analysis was installed according to testing layer references shown in Table 7. Similar to the wall test setup, thermocouple sensors were placed in the center of calorimetric environmental chamber Room A and along the north, south and east walls for room monitoring and data analysis.

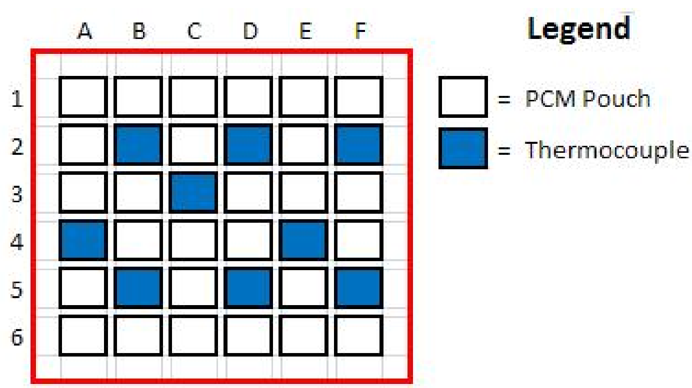


Figure 16. Plenum Test Section Sensor Placement

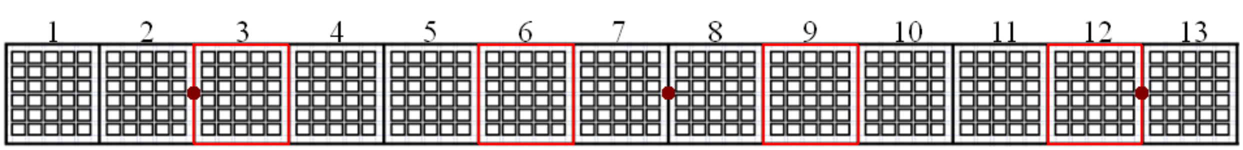


Figure 17. Plenum Sensor and Anemometer Placement

Table 7. Plenum Test Layer Configuration

Layer	Reference
Layer 1	Bio PCM mat exposed to inside of plenum
Layer 2	Fiberglass insulation exposed to backside of Bio PCM mat
Layer 3	Fiberglass insulation exposed to backside of gypsum wallboard
Layer 4	Gypsum wallboard exposed to calorimetric environmental chamber

The test matrix developed for the plenum air return distribution system test is shown in Table 8.

Table 8. Plenum Test Matrix

Run Order	Initial Room Temperature (°F)	Airflow Rate (CFM)
1	74	667
2	74	667
3	76	667
4	76	667
5	78	667
6	78	667
7	74	1300
8	74	1300
9	76	1300
10	76	1300
11	78	1300
12	78	1300
13	74	667
14	76	667
15	78	667

A matrix of test runs with 0.56-lb/ft^2 density, 2.0-lb/ft^2 density and baseline were conducted within the comfort zone range of 74–78 °F at two plenum airflow rates, 667 CFM and 1300 CFM, for a constant sensible heat load of 784 W. Data were collected for analysis to develop a thermal behavior and energy savings prediction model of the PCM mat for protracted periods of time in a typical building. As will be outlined in the results section, inconsistent results point to the need for further investigation of this application. It is unclear whether the difficulties arose due to insufficient PCM mass compared to the airflow or as a result of experimental testing error.

4. RESULTS/DISCUSSION

4.1. Wall Test Data Analysis

To establish a baseline, the calorimetric environmental chamber was set to hold a constant room temperature of 76 °F. The baseline temperature profile for each layer of each section was determined using the mean of the ten thermocouples installed in each layer of each section. Figure 18 shows the result of the baseline test. It was determined that the measured temperature variance was < ±1.5 °F.

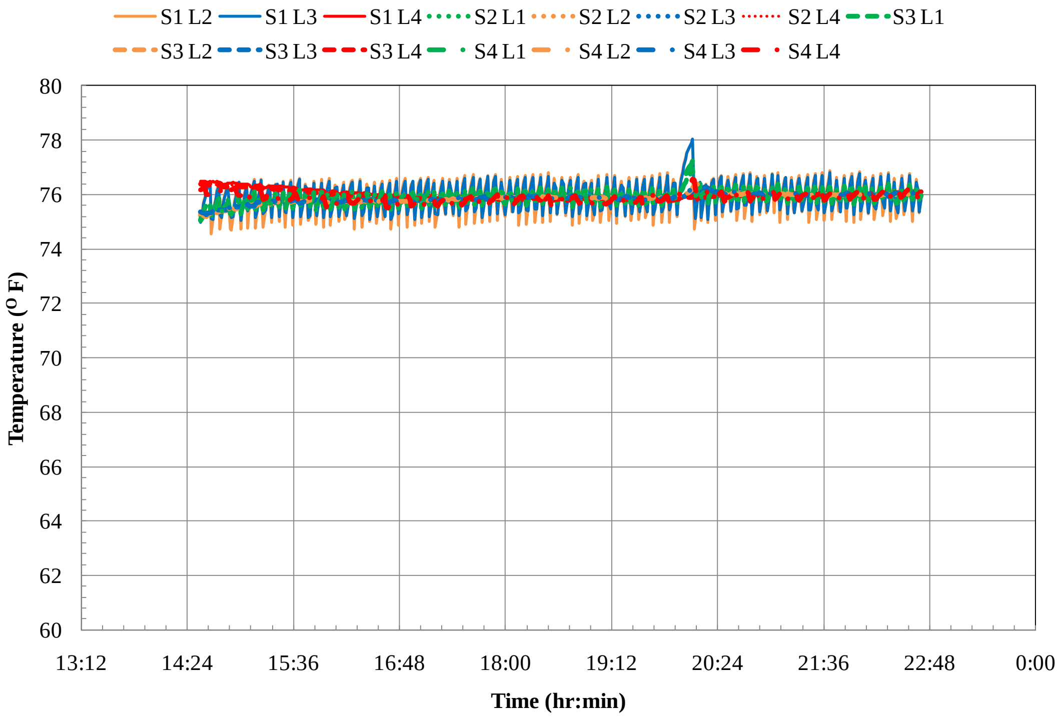


Figure 18. Baseline Data

The average heat flux was evaluated for each layer, and hence for the whole wall using Fourier's law of heat transfer:

$$q'' = \Delta T/R$$

where

q'' = Heat flux (heat rate per unit area), (BTU/ hr ft^2)
ΔT = Difference of temperatures across each layer, (°F)
R = Thermal resistance of the layer, (hr ft^2 °F /BTU)

Table 9 summarizes the R-value of each wall layer and overall R-value of the whole wall:

From the table, $R_{overall}$= 8.4 (m^2 °C/W), which corresponds to an R-value of 8.4*5.68= 47.712, or nearly R-48 (hr ft^2°F /BTU).

Table 9. R Values Calculated for Wall Layers

Construction Material	R-value(m^2 °C/W)	
	Between Studs	At Studs
1/8-in Plywood, R-0.155[1]	0.0273	0.0273
EPE Foam, Rigid insulation, R-30	5.28	5.28
Glass Fiber mat ins, R-19	3.35	--
6.25-in (2-in × 6-in) Wood studs, R-5.57	--	0.98
5/8-in Gypsum wallboard, R-0.545	0.096	0.096
Convection coefficient inside Room A[2]	0.12	0.12
Convection coefficient inside Room B	0.12	0.12
R for each section (total of the above)	8.9933	6.6233
U-factor for each section, **U=1/R** (W/ m^2 °C)	0.111	0.151
Area Fraction for each section, f_{area}	80	20
Overall U-factor, $U = \Sigma f_{area,i} * U_i = 0.8*0.111 + 0.2*0.151 = 0.119$	0.119 (W/m^2 °C)	
Overall wall thermal resistance = **1/U**	8.4 (m^2 °C/W)	

(1) From: "Heat Transfer, a Practical Approach", Yunus A. Cengel, McGraw–Hill, 1997, pp.978–980.
(2) From: "Heat Transfer, a Practical Approach", Yunus A. Cengel, McGraw–Hill, 1997, Table 12-10, p.726.

4.2. Wall Test Results

4.2.1. Comparison Wall Test Results

Figures 19 through 33 show the results of the 15 cases in the comparison wall test matrix, shown in Table 4. Each graph compares the average surface temperature (Layer 1) versus time for Wall Sections 2, 3 and 4 (see Table 5). Each test was performed twice.

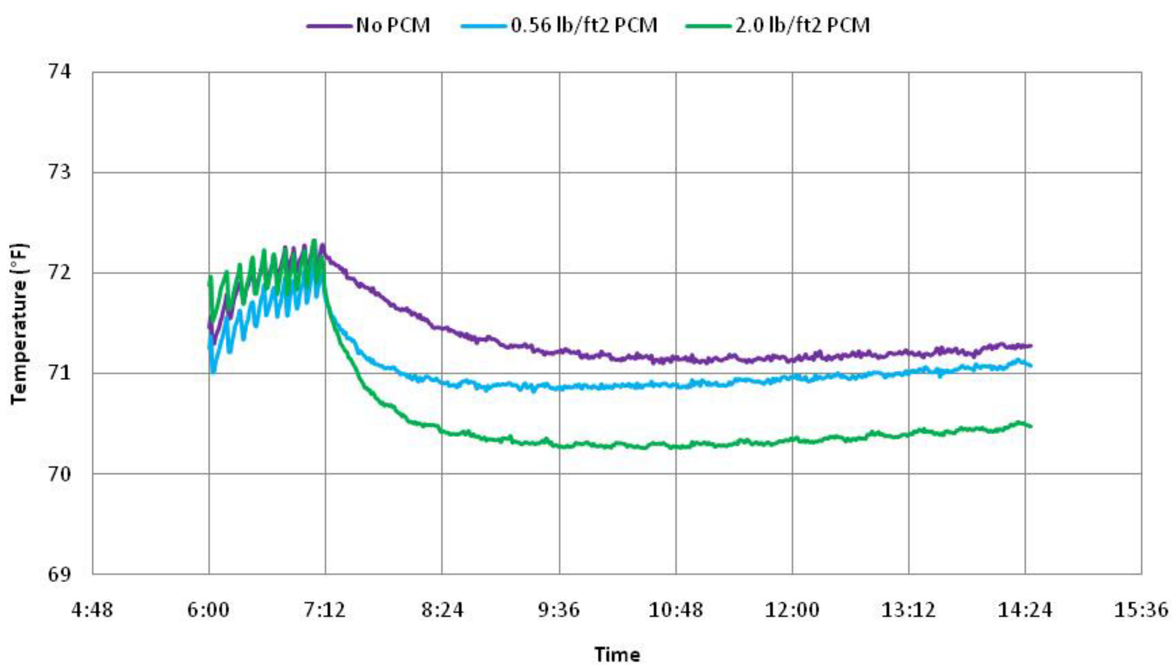


Figure 19. 100-W Comparison Wall Test from 74 °F—Run 1

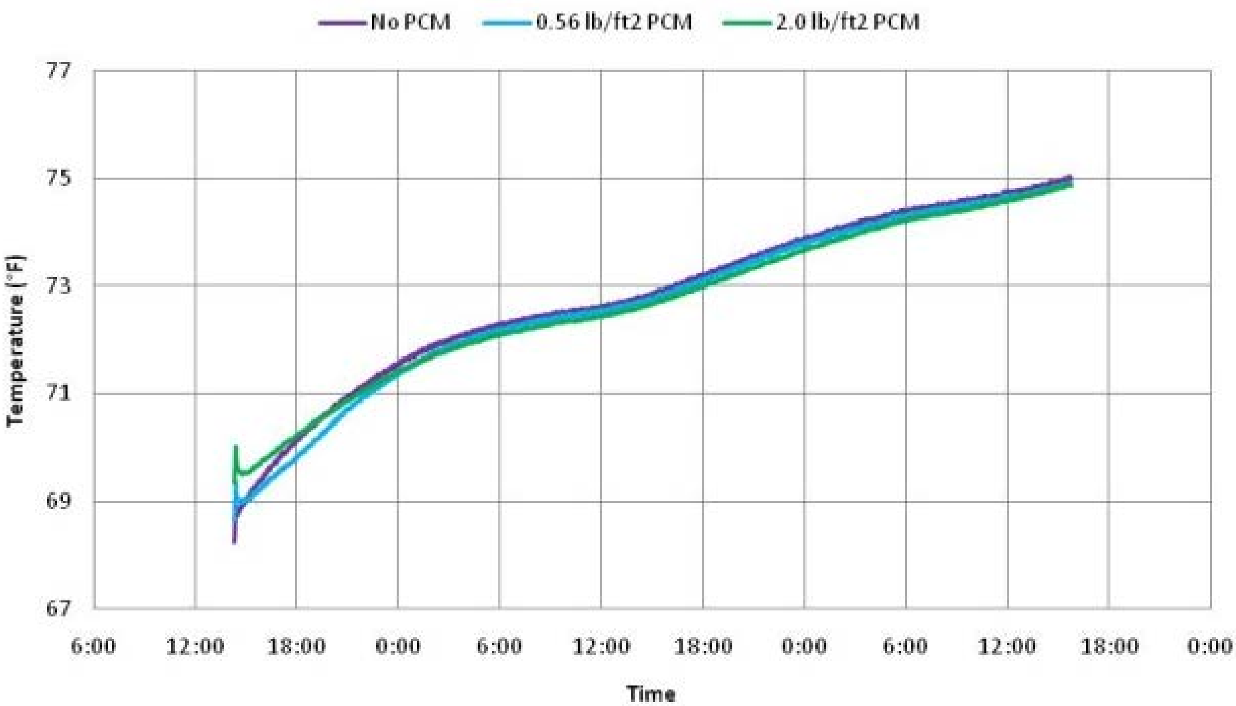


Figure 20. 100-W Comparison Wall Test from 74 °F—Run 2

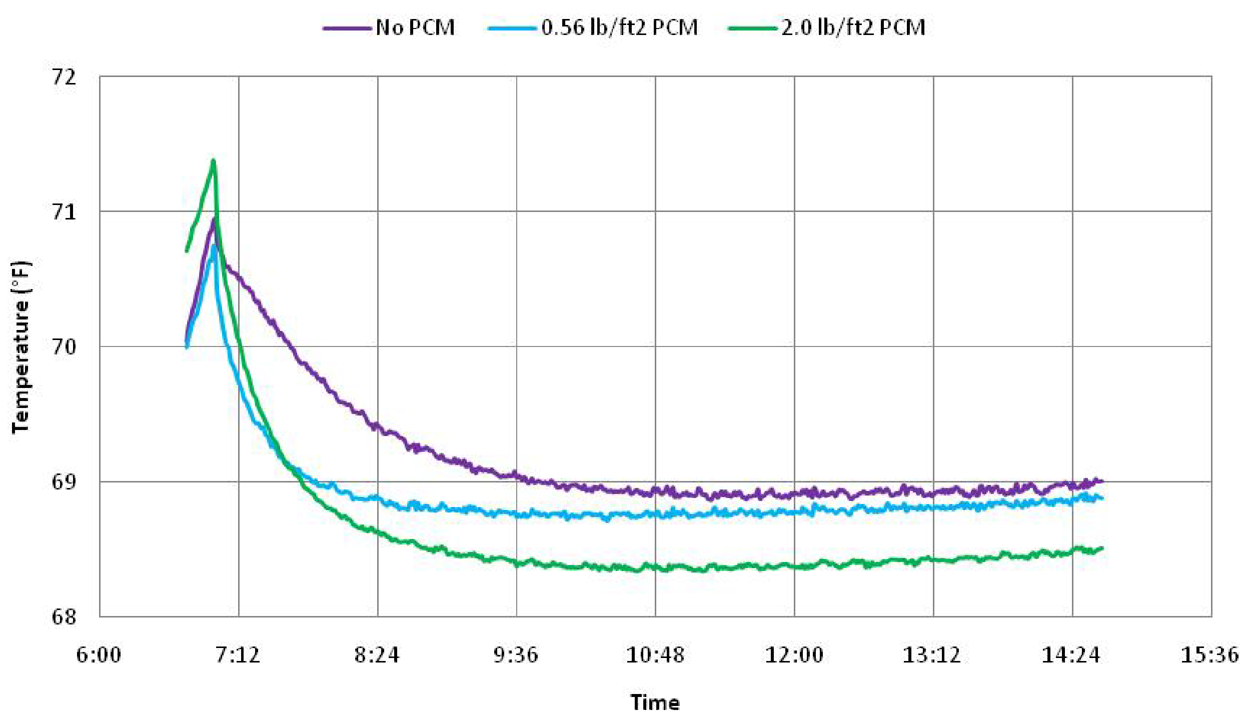


Figure 21. 100-W Comparison Wall Test from 76 °F—Run 1

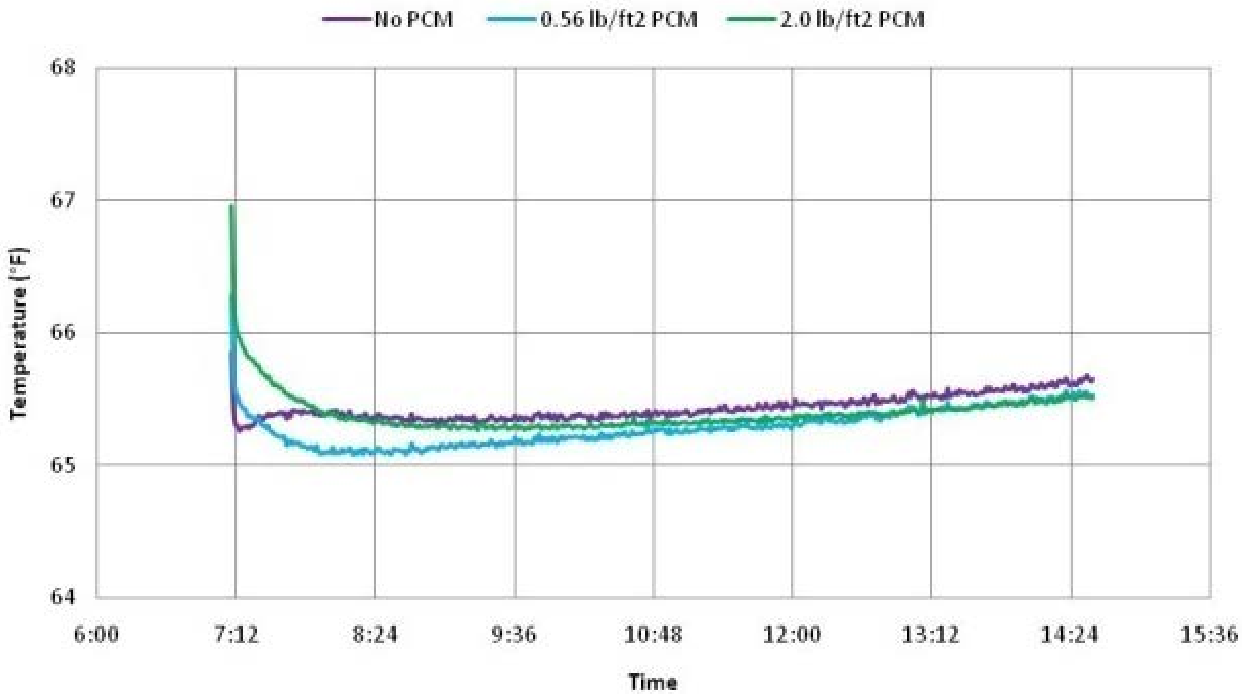


Figure 22. 100-W Comparison Wall Test from 76 °F—Run 2

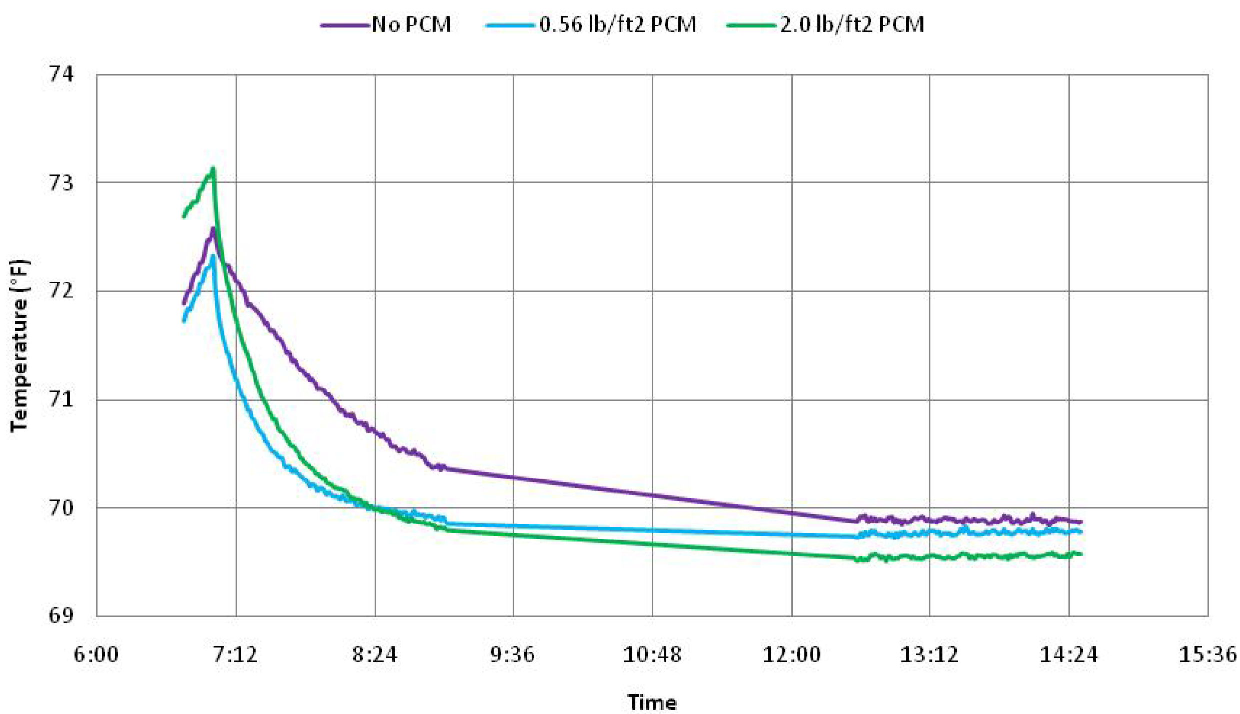


Figure 23. 100-W Comparison Wall Test from 78 °F—Run 1

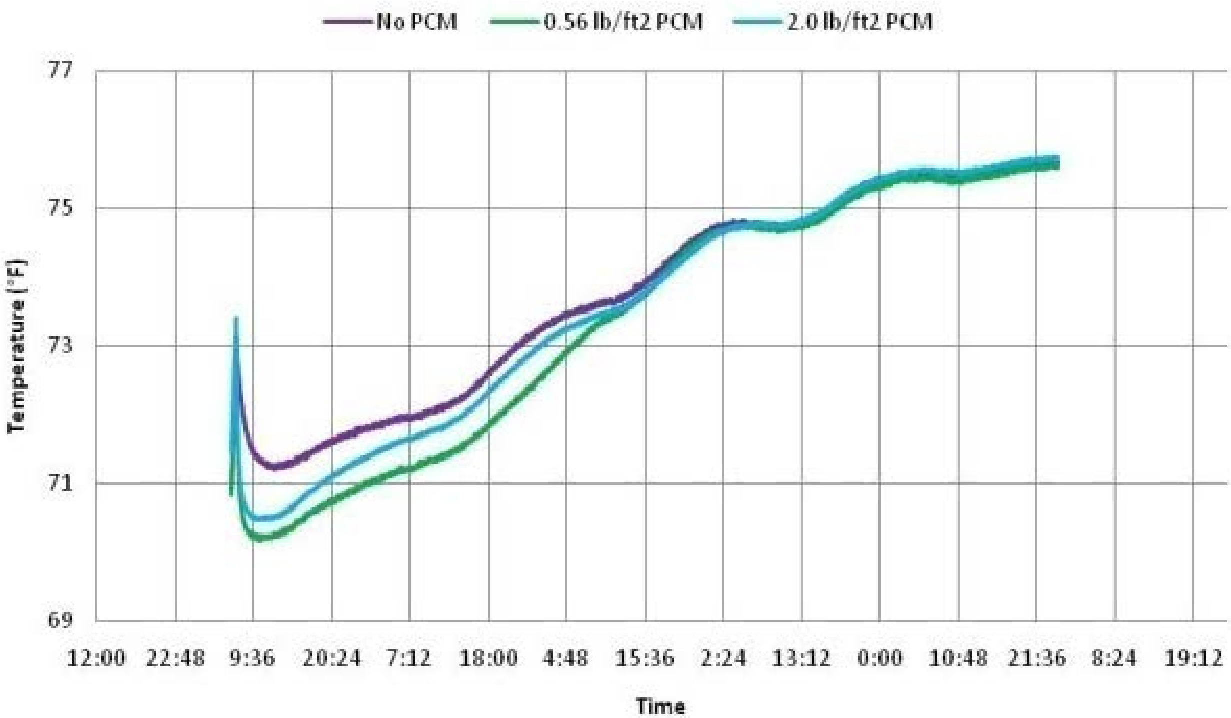


Figure 24. 100-W Comparison Wall Test from 78 °F—Run 2

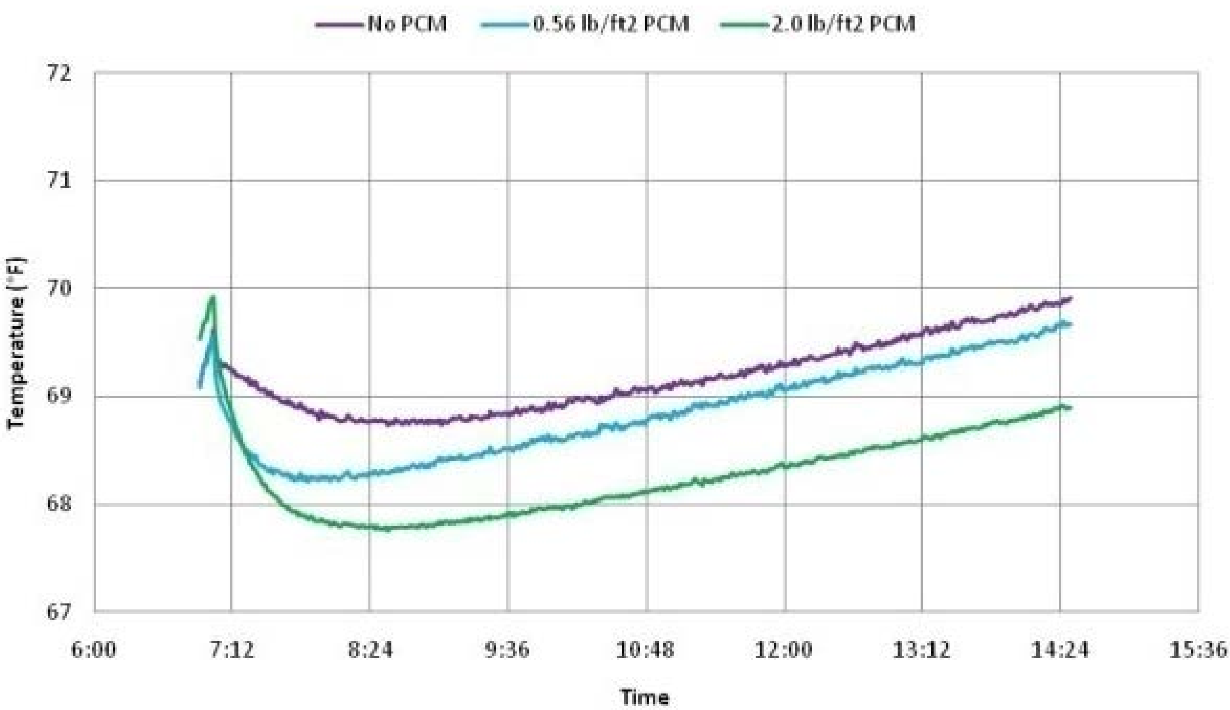


Figure 25. 250-W Comparison Wall Test from 74 °F

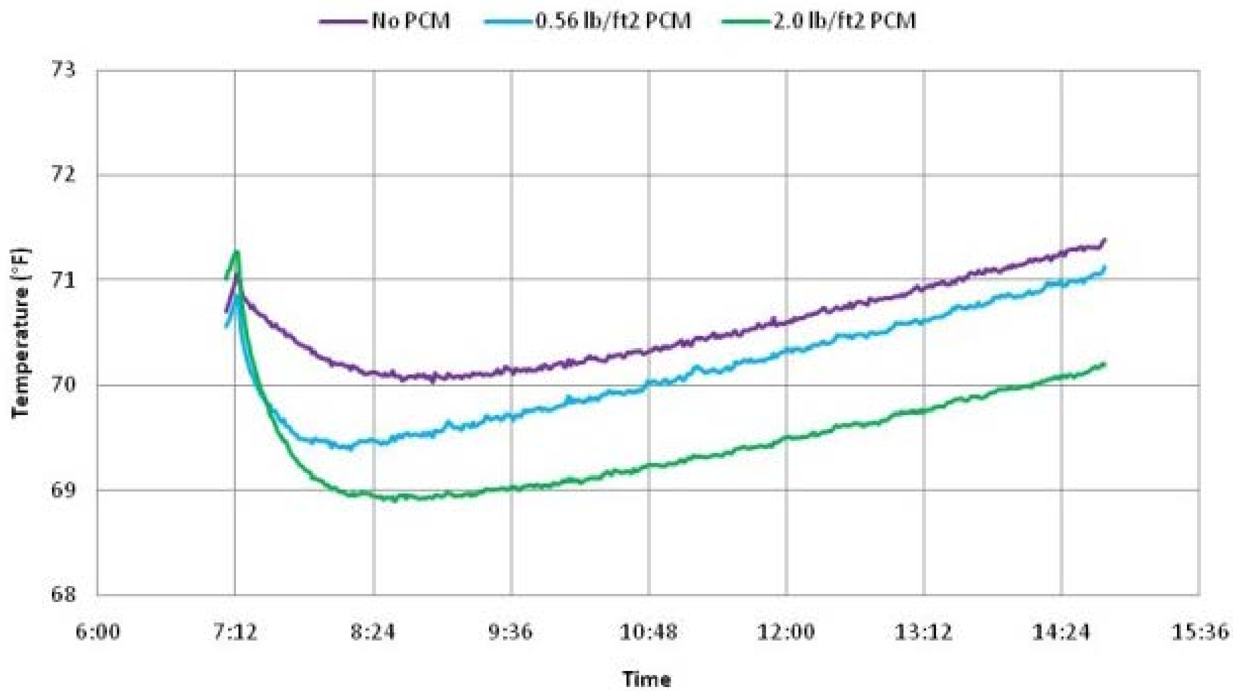


Figure 26. 250-W Comparison Wall Test from 76 °F

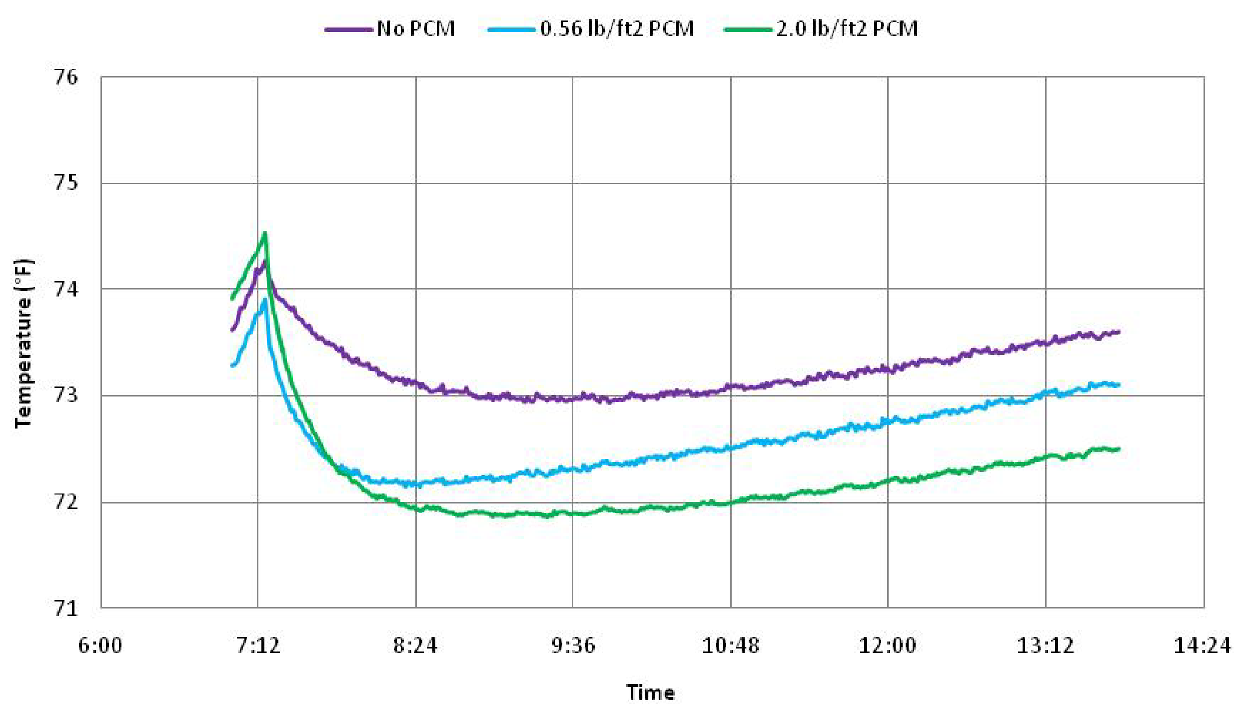


Figure 27. 250 W Comparison Wall Test from 78 °F

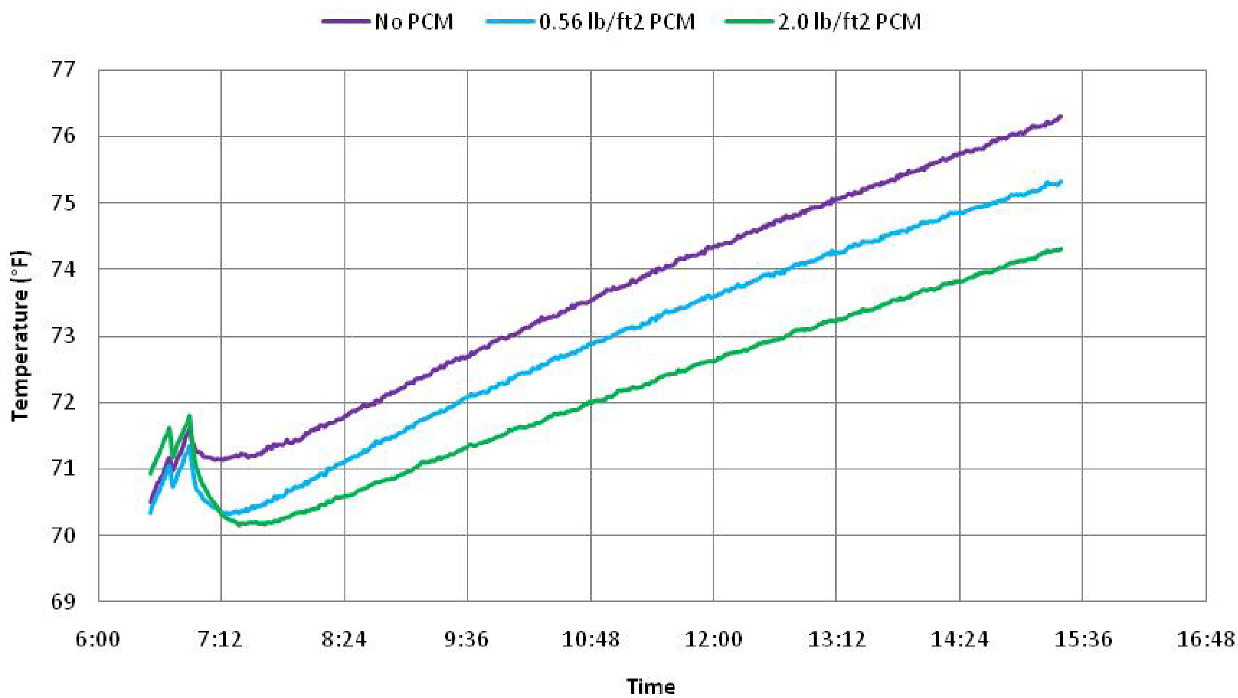


Figure 28. 400-W Comparison Wall Test from 74 °F—Run 1

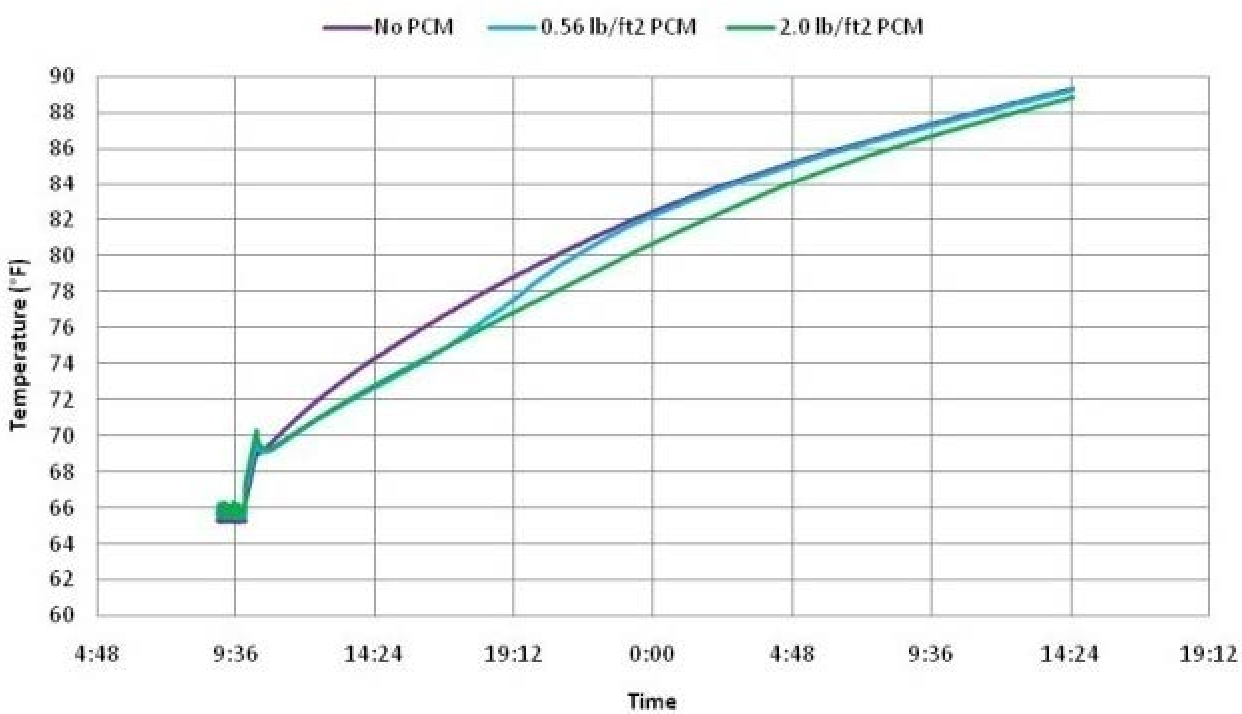


Figure 29. 400-W Comparison Wall Test from 74 °F—Run 2

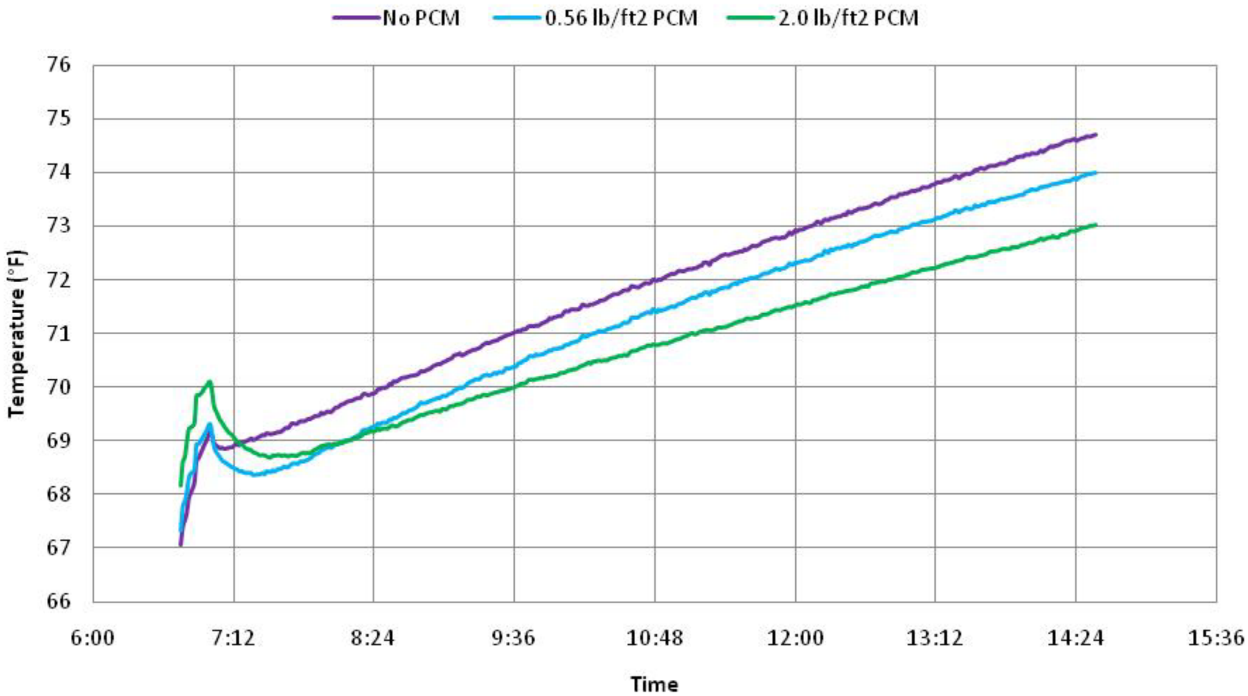


Figure 30. 400-W Comparison Wall Test from 76 °F—Run 1

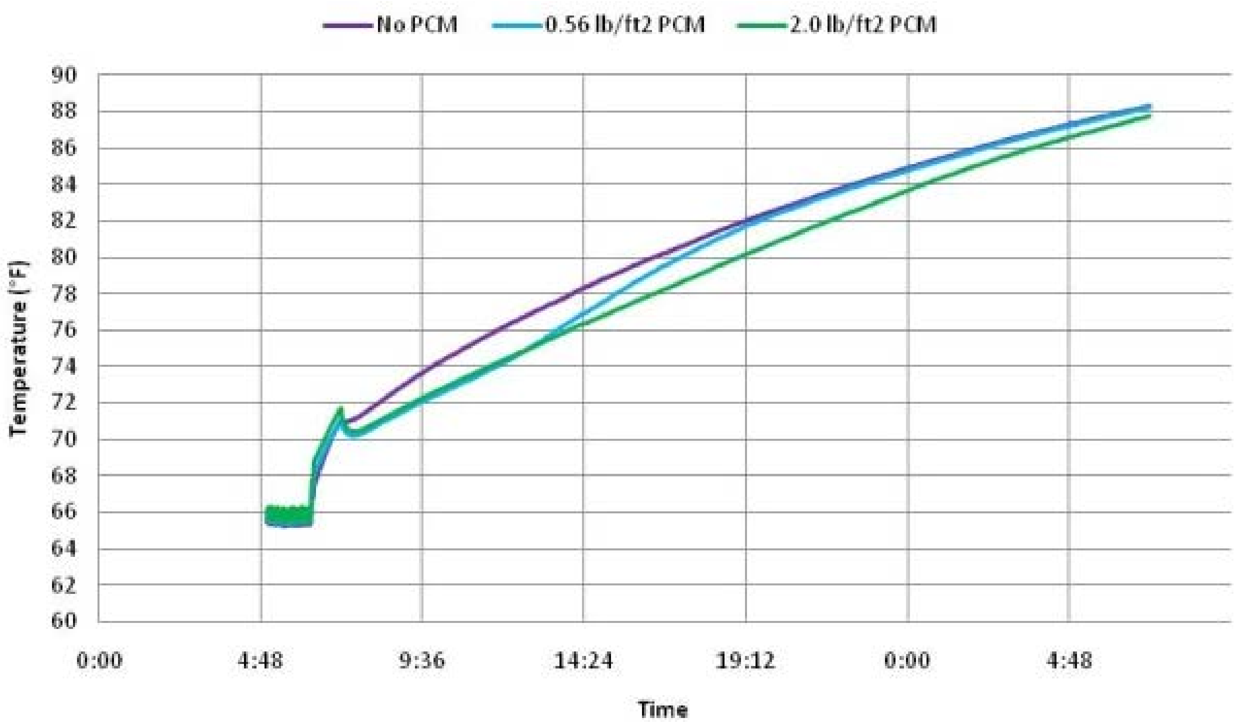


Figure 31. 400-W Comparison Wall Test from 76 °F—Run 2

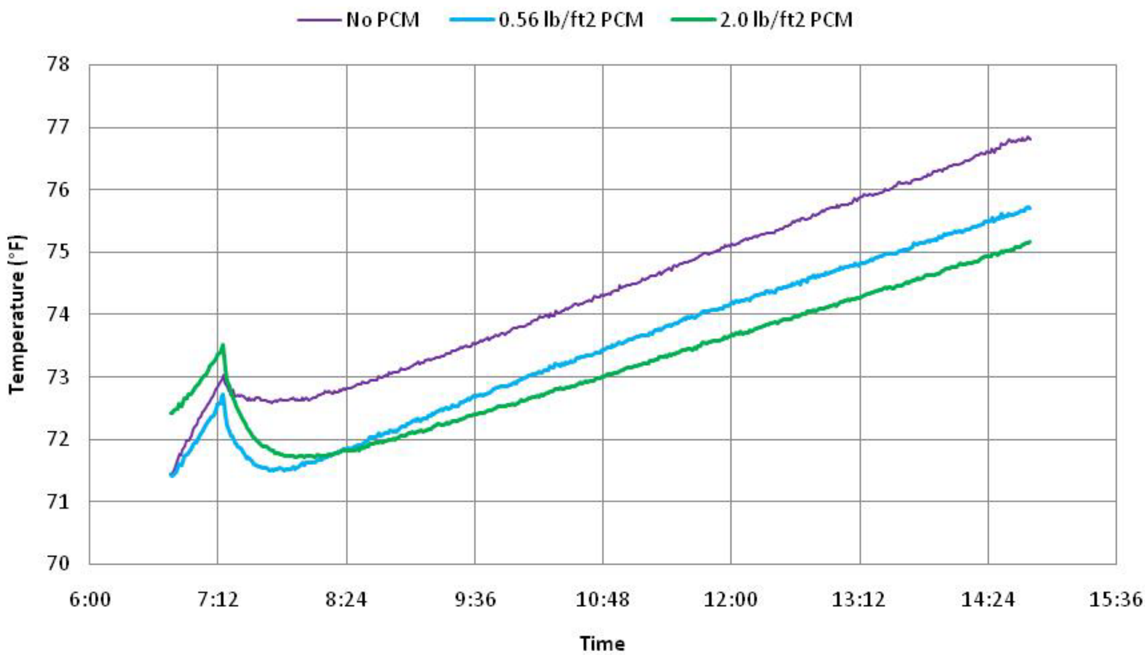


Figure 32. 400-W Comparison Wall Test from 78 °F—Run 1

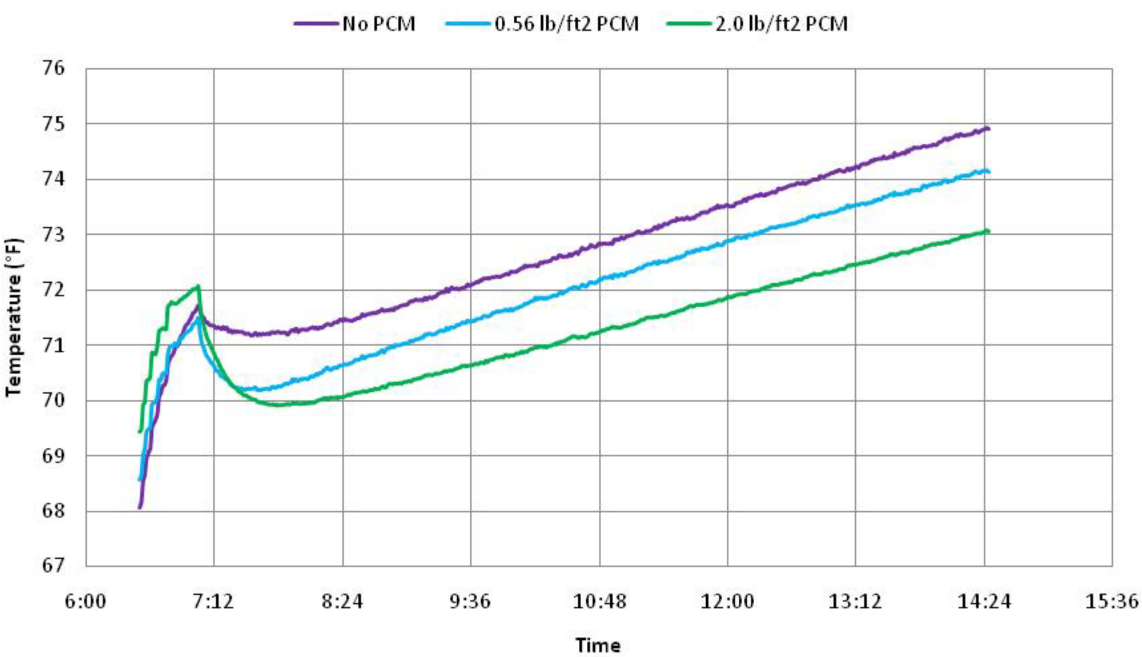


Figure 33. 400-W Comparison Wall Test from 78 °F—Run 2

The data show that using the PCM results in increasing the time for the outer wall to reach a given temperature, demonstrating the effect of the latent heat of fusion of the PCM material. For example, if we were to look at the time differential to reach 74 °F for the 400-W/78 °F test (as shown in Fig. 32), it can be observed that the time delay is approximately three hours. This analysis is shown in Figure 34.

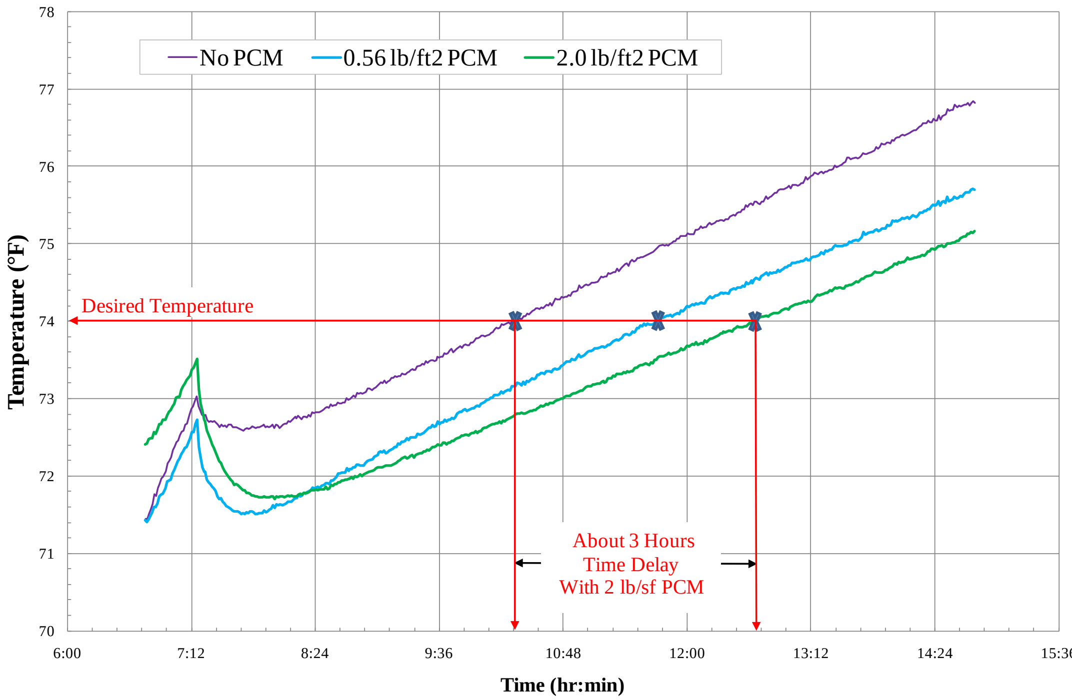


Figure 34. Results of 400-W Wall Comparison Test from 78 °F

4.2.2. 2.0-lb/ft^2 Wall Test Results

Figures 35–37 show the results of implementing the 2.0-lb/ft^2 PCM materials in the entire test wall, compared to the case without PCM for different interior loads as specified in the test matrix. If we again focus on the 400-W test cases, the time delay to achieve a given temperature is approximately 3 hours.

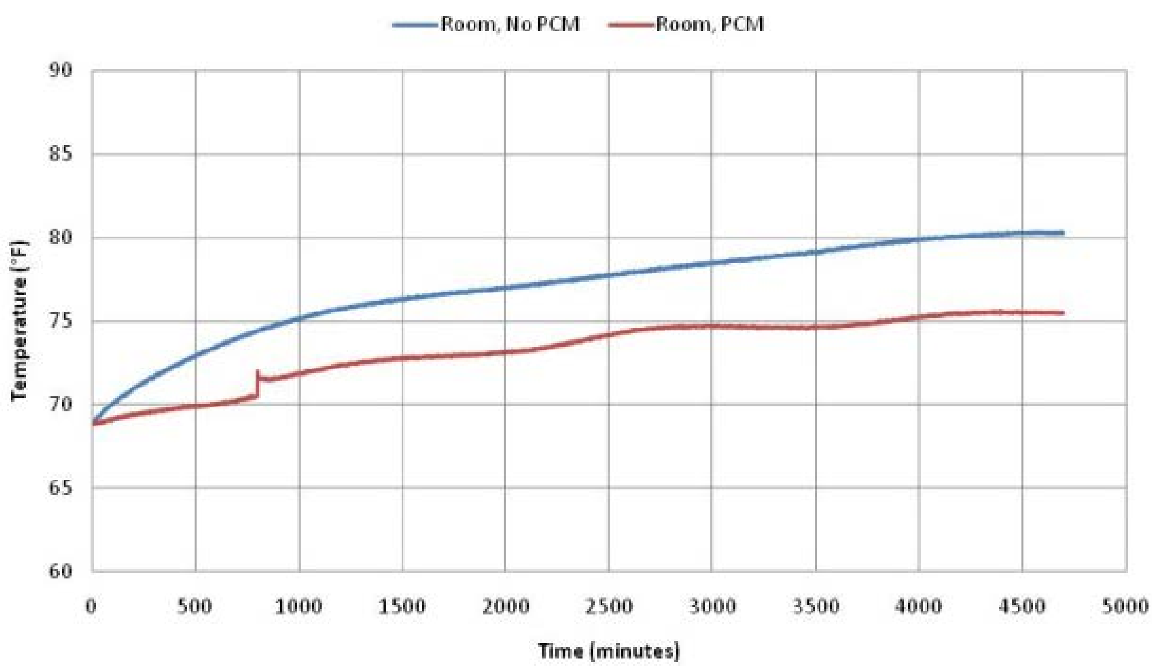


Figure 35. 2.0-lb/ft^2 100-W Test

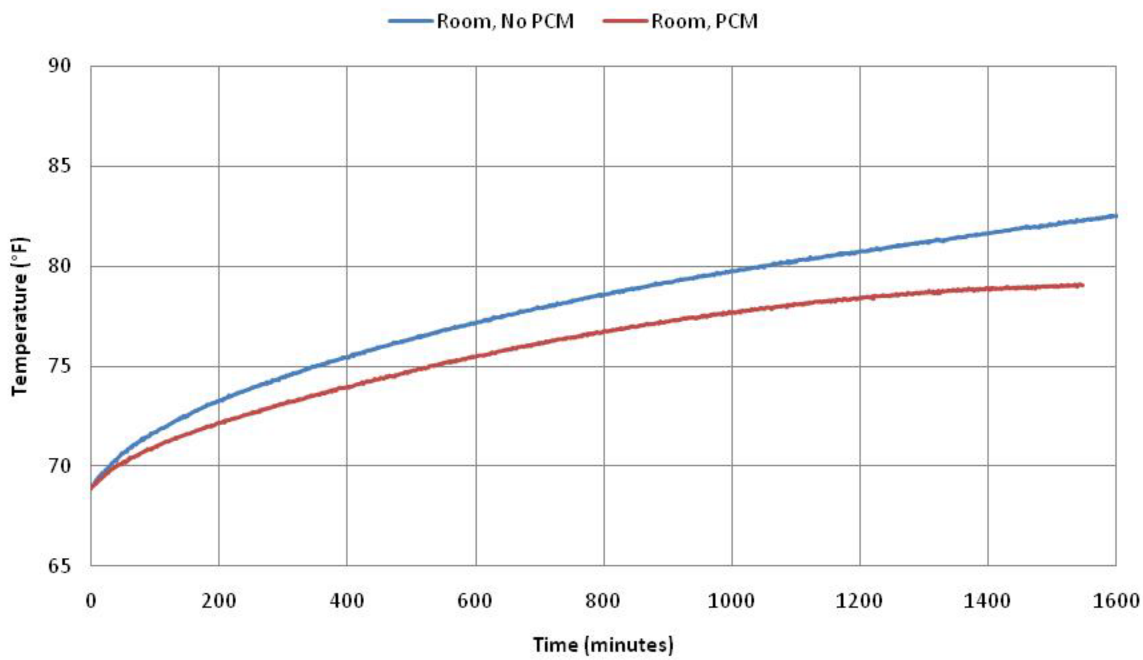


Figure 36. 2.0-lb/ft^2 250-W Test

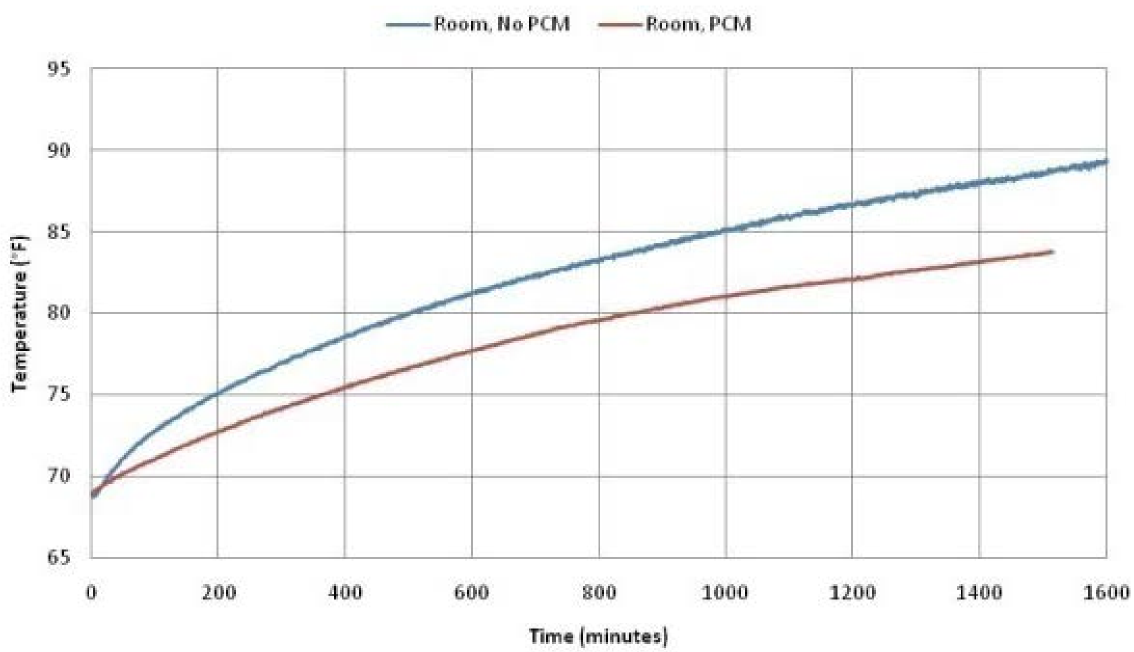


Figure 37. 2.0-lb/ft^2 400-W Test

This confirms that PCM can be used to add effective thermal mass to a structure, which can be used to peak-shift demand (i.e., move peak demand to a different part of the day). Peak shifting is especially effective when applied to an air handling system with economizers, experiencing bi diurnal temperature swings. In this way, the cool nighttime air provides free cooling to the PCM, which can then be used to reduce air conditioning demands during the hottest part of the day.

The sample data shown in Figures 38–41 compare layer temperature performance profiles over time of a typical wall setup with and without 2.0-lb/ft^2 PCM density installed in the wall cavities for given thermal loads. The data in Figures 38–41 indicate PCM in a typical wall cavity result in an increase of time for the outer wall and subsequent layers to reach a given temperature, demonstrating the effect of the latent heat of fusion of the PCM material and the viability of using PCM as an effective means of peak shifting or reduction in equipment capacity.

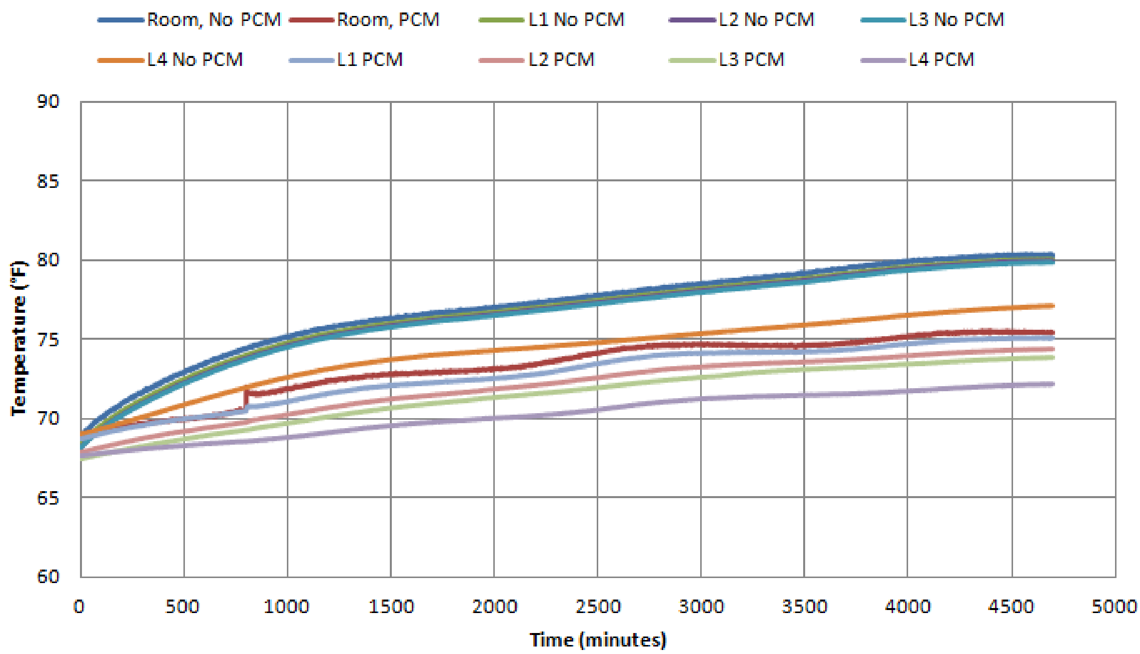


Figure 38. Layer Temperatures of No PCM and 2.0-lb/ft^2 PCM at 100 W

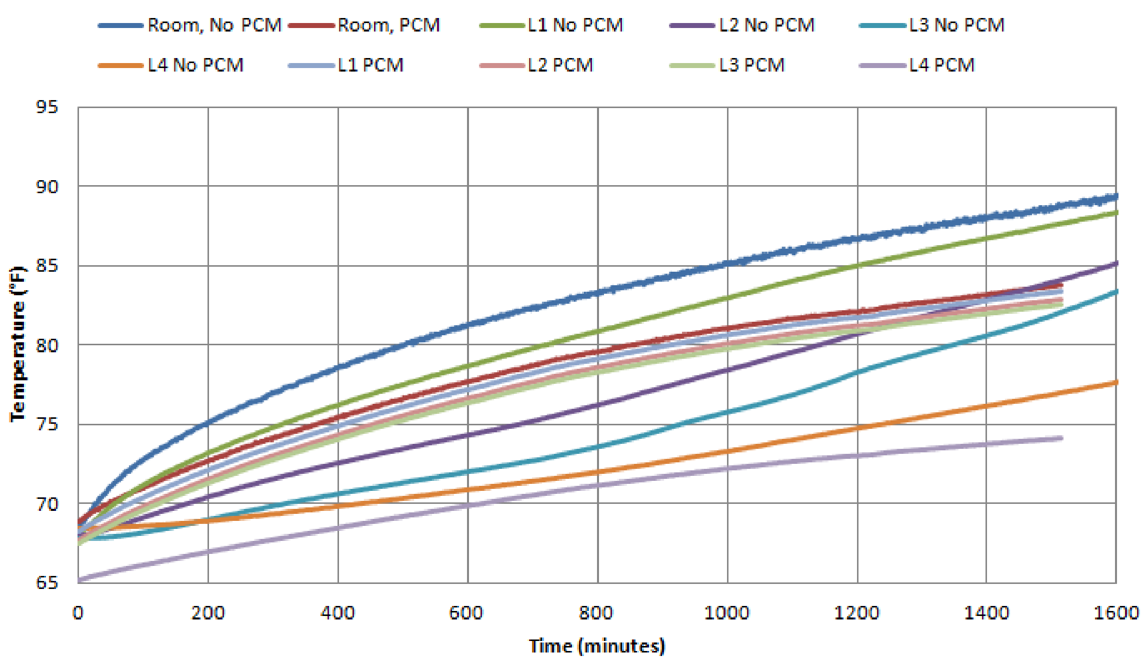


Figure 39. Layer Temperatures of No PCM and 2.0-lb/ft^2 PCM at 250 W

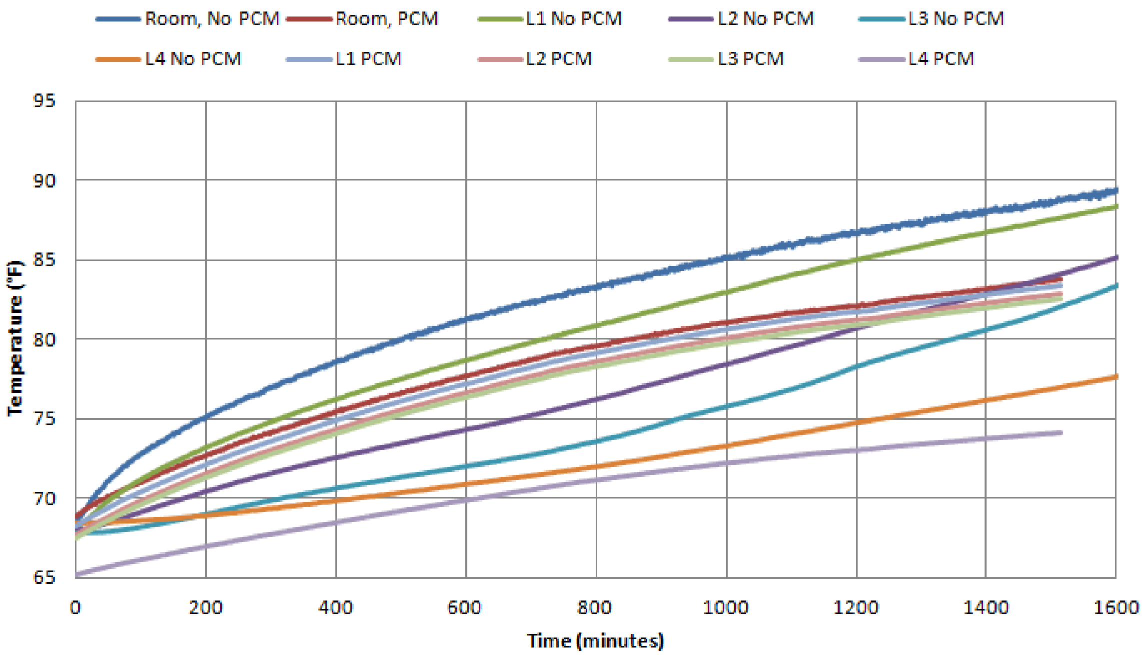


Figure 40. Layer Temperatures of No PCM and 2.0-lb/ft^2 PCM at 400 W

4.3. Plenum Test Data Analysis

To establish a baseline, the calorimetric environmental chamber was set to hold a constant room temperature of 74–78 °F in accordance with the plenum test matrix highlighted in Table 8. The baseline temperature profile for each layer of the plenum was determined as the mean value from the nine thermocouples installed in each layer of each section. Measured temperature variance was < ±1.5 °F. A matrix of test runs with 0.56-lb/ft^2 density, 2.0-lb/ft^2 density and baseline were conducted within the comfort zone range of 74–78 °F at two plenum air flow rates, 667 CFM and 1300 CFM, under a constant sensible heat load of 784 W. The 784-W sensible heat load and optimized 667-CFM volumetric airflow were calculated as the scaled cumulative lighting, process, and human load for the dimensions of the environmental chamber based on initial calculations of a room 20 ft × 20 ft × 10 ft and an office building air change rate of 10 per hour.

4.4. Plenum Test Results

Figures 41–43 show the results of installing 0.5-lb/ft^2 and 2.0-lb/ft^2 densities of PCM materials in a HVAC air return distribution system. These results were compared to baseline cases without PCM for a comfort zone temperature range of 74–78 °F, an air volumetric flow rate of 667 CFM and sensible heat load of 784 W.

Tests were also conducted with a 1300-CFM volumetric flow rate in accordance with the test matrix shown in Table 8. These tests, however, showed unexpected results—small, statistically nonsiginficant changes in room temperature when PCM was installed in an air return system and compared to an air return distribution system with no retrofitted PCM material. It is unclear whether the results were due to experimental error, poor heat transfer between the air and PCM, or insufficient PCM thermal mass compared to the air flow rate.

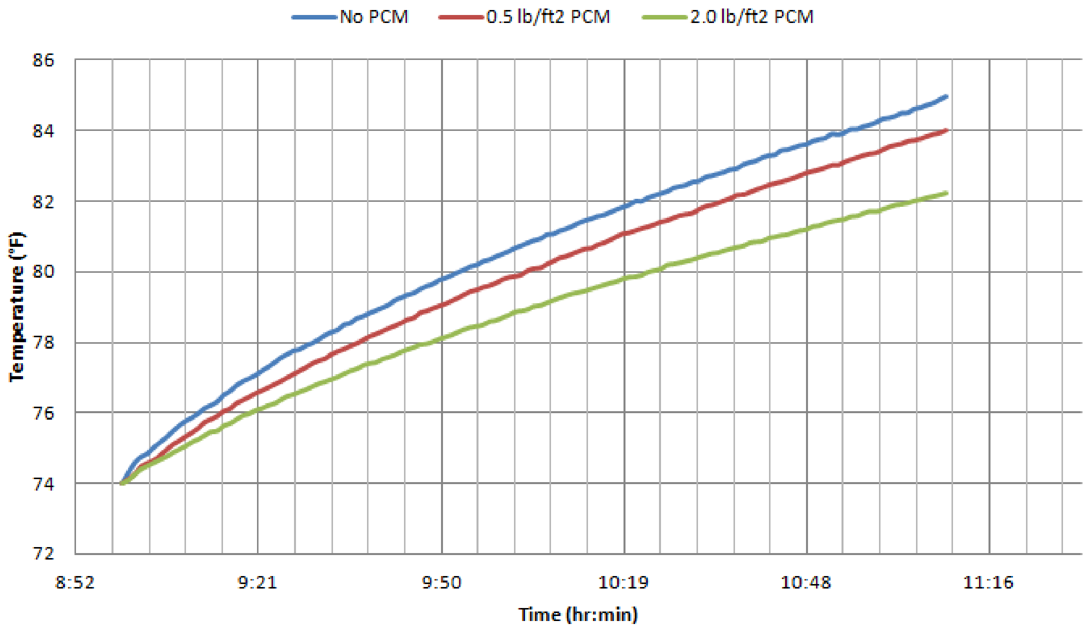


Figure 41. Temperature Rise during 74 °F, 667-CFM, 784-W Plenum Tests

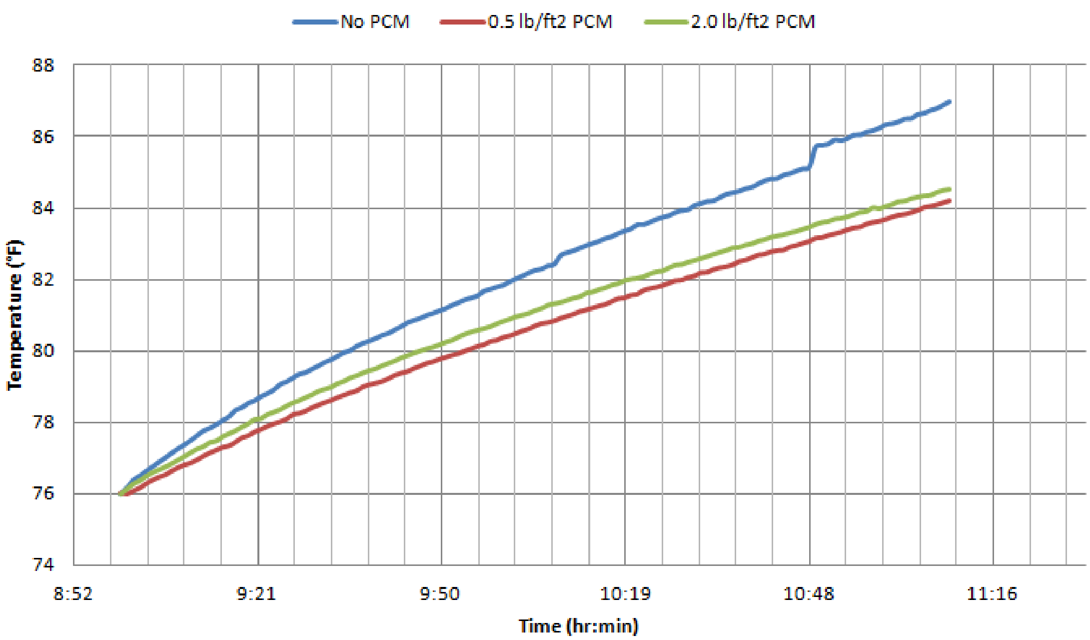


Figure 42. Temperature Rise during 76 °F, 667-CFM, 784-W Plenum Tests

Despite inconsistencies in the data and noted potential errors identical to the 1300-CFM tests, data sets shown in Figures 41–43 for the 667-CFM tests generally support the conclusion that PCM may be used to add effective thermal mass to an air return distribution system and a typical building setup. At all three comfort zone set-point temperatures, there was a reduction in heated room temperature with PCM installed in the air return when exposed to extended periods of a thermal load compared to a setup with no PCM installed.

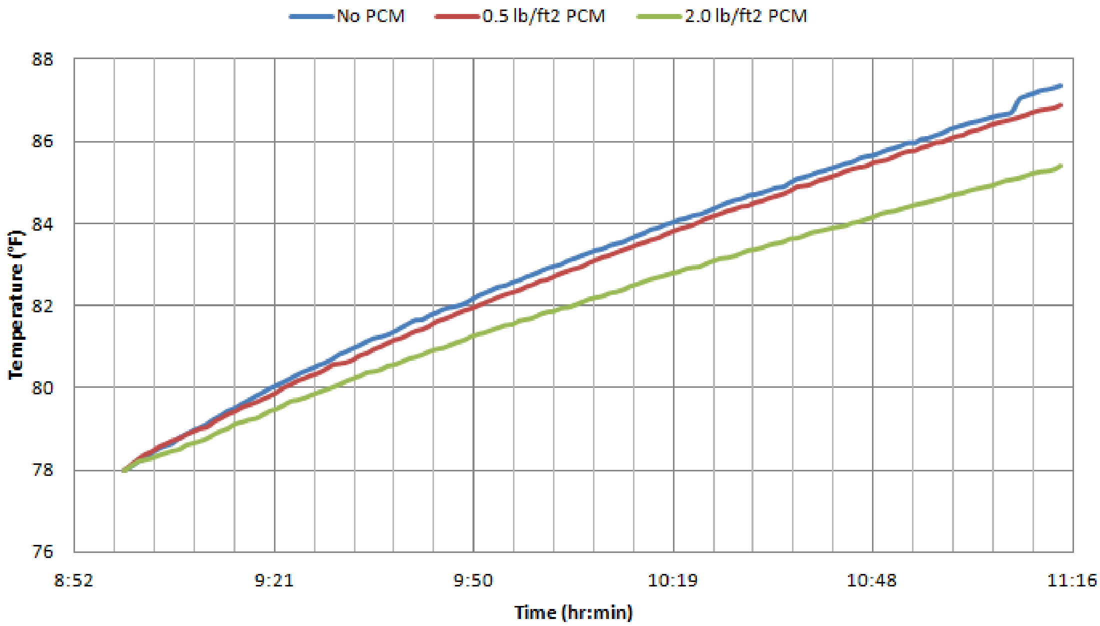


Figure 43. Temperature Rise during 78 °F, 667-CFM, 784-W Plenum Tests

With inconclusive data and results, further investigation and testing is needed in applications with PCM material installed into an air return distribution system. Understanding of heat transfer and transient thermal characteristics of the PCM material exposed on one side to a boundary condition of high air flow rates and a boundary condition of a sensible heat load on the other side is needed to fully optimize the required PCM density at a desired comfort zone set-point temperature to reduce and peak shift the thermal demand to desired user levels.

5. COMPUTATIONAL ANALYSIS

5.1. PCM Estimate

An Excel spread sheet to estimate the amount of PCM needed for free cooling of a building and to determine the payback period is provided as Appendix A to this report. Further details about using the tool are documented within the spreadsheet.

5.2. Computational Model Development

The computational model simulates a building with wall(s) and/or ceiling outfitted with PCM as one of the layers. The model includes nonlinear terms arising from simulation of the heat transfer through the PCM layer. The energy balance equations are solved numerically. First, for heat transfer through composite layers of a wall or a ceiling as shown in Figure 44, the heat transfer analysis is based on the transient heat conduction equation for a multidimensional Cartesian-coordinate system expressed as follows:

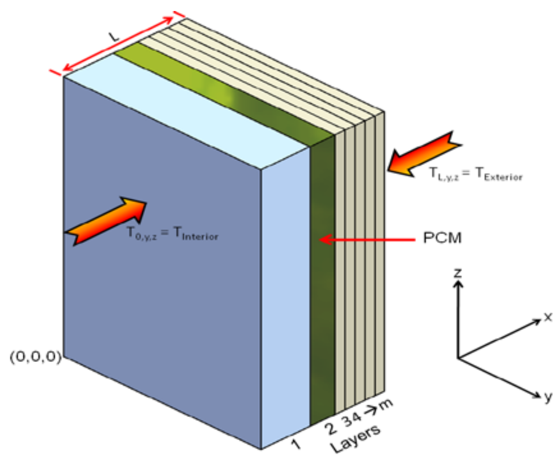


Figure 44. Layered Wall/Ceiling with PCM

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (K \nabla T) - \rho L \frac{\partial g}{\partial t}$$

where

T = Temperature
t = time
ρ = Layer's density
C_p = Layer's specific heat
K = Layer's thermal conductivity
g = PCM heat source term
L = PCM latent heat

and ∇ is the three-dimensional del operator, defined for a Cartesian coordinates system as $\hat{\boldsymbol{x}}\frac{\partial}{\partial x} + \hat{\boldsymbol{y}}\frac{\partial}{\partial y} + \hat{\boldsymbol{z}}\frac{\partial}{\partial z}$, where $\hat{\boldsymbol{x}}$, $\hat{\boldsymbol{y}}$ and $\hat{\boldsymbol{z}}$ are the unit vectors in their respective directions.

The wall is exposed from one side to a boundary condition representing the interior side of the wall, with an initial room temperature, set point temperature of the air conditioning, air change rate for ventilation, and known heat transfer coefficient for the air. The other side of the wall is exposed to the exterior ambient conditions, with known weather data for the specific location. Second, for room and attic heat transfer analysis, a heat balance will be applied to calculate the room temperature. The heat balance follows the first law of thermodynamics by considering the attic as a system and the room as previously indicated. For this system, the overall heat balance can be written as follows:

$$\frac{\partial Q}{\partial t}\Big|_{\text{system}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} + \dot{Q}_{\text{gen}}$$

All the energy components for the system are represented as boundary conditions. These include solar heating; night cooling; attic air circulation; convection; radiation; solar heating through windows; heat from people, lights, and equipment; known air change rate for ventilation, and the air conditioning settings. All these components are shown in Figure 45.

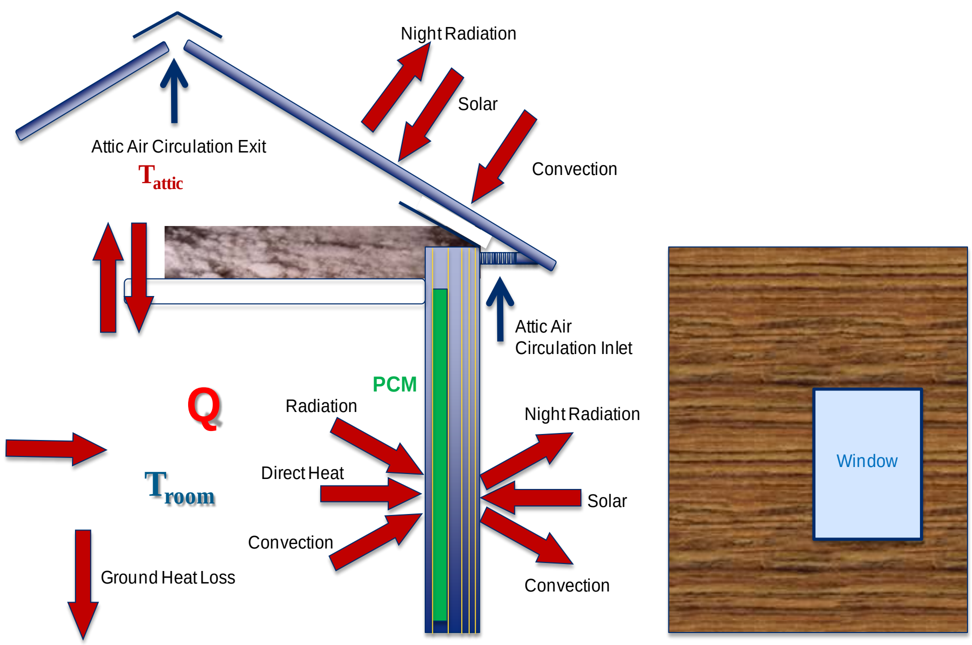


Figure 45. Room and Attic Heat Transfer Balance

The following parameters must be specified for the model to solve for room temperature as a function of time:

➢ <u>Material Properties for wall/ceiling layer and for windows:</u>

ρ = Layer's Density
C_p = Layer's Specific Heat
K = Layer's Thermal Conductivity
T_m = PCM melting temperature
L = PCM Latent Heat

In addition, the emissivity, absorptivity and reflectivity of the material, air properties, and heat transfer coefficients for the inside and outside of the structure envelope must also be specified.

➢ <u>Weather data for the specific location:</u>
The simulation model is linked to a Solar Path model, which retrieves weather data for the location and accurately calculates the total solar radiation incident on a tilted surface at any orientation and at any time, as illustrated in Figure 46. This allows modeling of any structure anywhere and provides file data for the user's location to execute the PCM simulation.

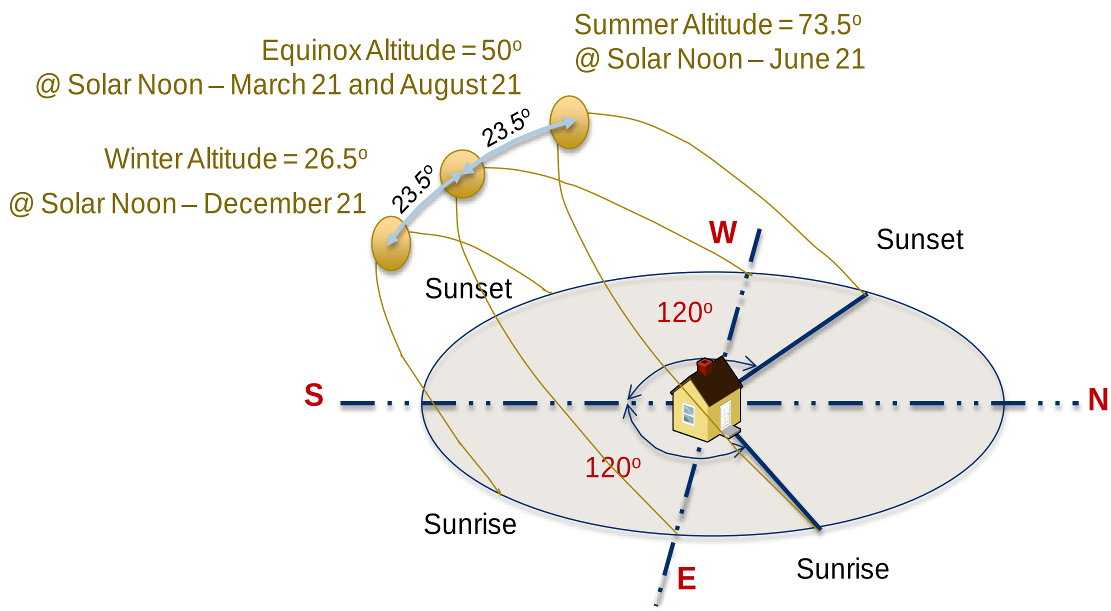


Figure 46. Computational Model—Solar Path

5.3. Simulating a Building

The folder on the enclosed CD titled: "Expert Tool for Phase Change Material Design" is provided to assist engineers and architects to simulate implementing PCM in the walls and/or ceiling of a building and give recommendations for optimum use of the PCM materials in structures.

The folder has five files as follows:

(1) "pcm.exe" is the executable file, which the user will click on to start the analysis.
(2) "Materials.csv" is required for the executable file. It retrieves materials information for the structure based on the user's choice. The user assigns a number to each layer of wall and ceiling and a number to each window type, etc., for the building's materials and modifies the sample data files: test6r.dat and trst6rnpcm.dat following the same format of the sample data.
(3) "TYNDALLAFB.dat" is a sample of the weather data of Tyndall AFB; the user will replace this file with the appropriate base weather data file, which will be provided by the code developer upon request.

(4) “test6r.dat” is a sample of the user data for analysis of the structure outfitted with PCM in the walls and or ceiling. The user will modify this file to contain problem-specific data, following the sample format.
(5) “test6rnpcm.dat” is a sample of the user data for analysis of the structure without PCM in the walls and or ceiling. Again, the user will modify this file to contain problem-specific data following the sample format.

Both samples of user data were designed for a building with dimension of 200 cm × 200 cm floor area. Each wall is composed of four layers and each wall has a 90-cm^2, single-pane glass (standard clear) window. The room has a ceiling and a gable roof (four roof sides, two at 30° tilt, and two at 90° tilt on the horizontal level), ceramic tile floor and 25 °C ground temperature. A 1000-W, internal, sensible heat load and five air change per hour were used for the simulation.

The program calculates the temperature distribution and estimates the indoor temperature as a function of time. Comparison of the results with and without PCM indicates the relative energy savings for a given application. Comparison of installed costs versus energy cost can then be made to determine a business case for PCM on a case-by-case basis.

Table 10 shows the listing of the “test6r.dat” The lines before the actual data numbers explain what the expected data are and what needs to be replaced by the actual data introduced by the user following the sample format:

Table 10. Data File Inputs

Expected Data	**Sample Data Input**	**Notes**
File name for solar props	TYNDALL AFB.dat	upon request, code developer will provide user’s file name for his/her base location, which will replace TYNDALL AFB.dat
Convergence accuracy, maximum iteration	1.0e-6, 100000	very good numbers—need no change
Year, month, day, hour, number of time steps, delta time	2010,7,1,12, 50, 10.0	a chosen time to start the simulation, number of time steps, and the transient time division
First Wall—azimuth is the angle measured from due north to the wall facing direction; here the wall is facing south, so azimuth is 180^{o}. Follow for other walls		
Wall area (cm^2), azimuth (facing south)	40000, 180	
Number of windows	1	
Window type, window area (cm^2)	1, 90	number for window type from Materials.cvs file for user choice
Initial temperature	22.0	
First *x* region width, number of intervals (1D, no *y* or *z*)	1.59, 10	actual width, in cm, of first layer in *x*-direction, and number of nodes for analysis
Second *x* region width, number of intervals (1D, no *y* or *z*)	1.35, 20	next layer in *x*-direction, and nodes

Third *x* region width, number of intervals (1D no *y* or *z*)	15.875, 10	next layer in *x*-direction, and nodes
Fourth *x* region width, number of intervals (1D, no *y* or *z*)	10.16, 10	next layer in *x*-direction, and nodes
End *x* regions	0.0,0	Flag—entering zero values ends the layers
Material for region 1	21	
For region 1, 1, 1 to 10, 1, 1	1,1,1,10,1,1	specifies what nodes occur in this layer (based on the number of intervals chosen above). **Comment also applies for regions 2–4 below**
Material for region 2	46	
For region 11, 1, 1 to 30, 1, 1	11,1,1,30,1,1	
Material for region 3	25	
For region 31, 1, 1 to 40, 1, 1	31,1,1,40,1,1	
Material for region 4	7	
For region 41, 1, 1 to 50, 1, 1	41,1,1,50,1,1	
End region materials by entering 0	0	a flag—entering a zero value ends the layers' material choices
Second Wall—follow format above for the "first wall" but modify values for second wall		
Wall area (cm^2), azimuth (facing west)	40000, 270	
Number of windows	1	
Window type, window area (cm^2)	1, 90	
Initial temperature	22.0	
First *x* region width, number of intervals (1D, no *y* or *z*)	1.59, 10	
Second *x* region, width, number of intervals this (1D, no *y* or *z*)	1.35, 20	
Third *x* region, width, number of intervals (1D, no *y* or *z*)	15.875, 10	
Fourth *x* region, width, number of intervals (1D, no *y* or *z*)	10.16, 10	
End *x* regions	0.0,0	
Material for region 1	21	
For region 1, 1, 1 to 10, 1, 1	1,1,1,10,1,1	
Material for region 2	46	
For region 11, 1, 1 to 30, 1, 1	11,1,1,30,1,1	
Material for region 3	25	
For region 31, 1, 1 to 40, 1, 1	31,1,1,40,1,1	
Material for region 4	7	
For region 41, 1, 1 to 50, 1, 1	41,1,1,50,1,1	
End region materials by entering 0	0	

Third Wall—follow format above for the "first wall" but modify values for third wall		
Wall area (cm^2) and azimuth (facing north)	40000, 0	
Number of windows	1	
Window type, window area (cm^2)	1, 90	
Initial temperature	22.0	
First *x* region width, number of intervals (1D, no *y* or *z*)	1.59, 10	
Second *x* region, width, number of intervals this (1D, no *y* or *z*)	1.35, 20	
Third *x* region, width, number of intervals (1D, no *y* or *z*)	15.875, 10	
Fourth *x* region, width, number of intervals (1D, no *y* or *z*)	10.16, 10	
End *x* regions	0.0,0	
Fourth Wall—follow format above for the "first wall" but modify values for fourth wall		
Wall area (cm^2) and azimuth (facing east)	40000, 90	
Number of windows	1	
Window type, window area (cm^2)	1, 90	
Initial temperature	22.0	
First *x* region width, number of intervals (1D, no *y* or *z*)	1.59, 10	
Second *x* region, width, number of intervals this (1D, no *y* or *z*)	1.35, 20	
Third *x* region, width, number of intervals (1D, no *y* or *z*)	15.875, 10	
Fourth *x* region, width, number of intervals (1D, no *y* or *z*)	10.16, 10	
End *x* regions	0.0,0	
Material for region 1	21	
For region 1, 1, 1 to 10, 1, 1	1,1,1,10,1,1	
Material for region 2	46	
For region 11, 1, 1 to 30, 1, 1	11,1,1,30,1,1	
Material for region 3	25	
For region 31, 1, 1 to 40, 1, 1	31,1,1,40,1,1	
Material for region 4	7	
For region 41, 1, 1 to 50, 1, 1	41,1,1,50,1,1	
End region materials by entering 0	0	

Ceiling		
Ceiling area, ceiling–attic area	40000.0, 40000.0	ceiling–attic area should be a little less than ceiling area
Ceiling initial temperature	22.0	
First *x* region width, number of intervals	15.9, 40	very similar to wall layers
End *x* regions	0.0,0	
Material for region 1	21	
For region 1, 1, 1 to 40, 1, 1	1,1,1,40,1,1	
End region materials by entering 0	0	
Number of roofs	4	for gable roof
Roof 1		
Roof material, volume, area, tilt, azimuth, attic view form, initial temp	30,230940,23094, 30,180,1, 22	
Roof 2		
Roof material, volume, area, tilt, azimuth, attic view form, initial temp	30,57735,5773.5, 90, 270,1, 22	
Roof 3		
Roof material, volume, area, tilt, azimuth, attic view form, initial temp	30, 230940, 23094,30,0,1,22	
Roof 4		
Roof material, volume, area, tilt, azimuth, attic view form, initial temp	30,57735,5773.5, 90,90,1, 22	
Attic volume, fraction of air volume change per second, initial temperature	582494, 0.006, 22.0	
Room volume, air volume changes per hour, heat source, heat load, initial temp	2866314, 20,1000.0, 0.25,22	
Floor material, floor area, ground temperature,	37,40000, 25	

6. SUPPLEMENTAL TOOLS AND REPORTS

- Appendix A lists the Material Safety Data Sheet (MSDS) for the PCM product used in this study.

- Appendix B lists the “Report for testing surface burning characteristics of PCM materials, according to Standard # ASTM E-84”, by Intertek Testing Services NA, Inc. as a third party.

  Note: Based on the 2006 International Building Code, Section 803 Wall and Ceiling Finishes, Paragraph 803.1 states, “Interior wall and ceiling finishes shall be classified in accordance with ASTM E-84.” Such interior finish materials shall be grouped in the following classes in accordance with their flame spread and smoke-developed indexes:

  i. Class A: Flame Spread 0–25; Smoke-Developed 0–450
  ii. Class B: Flame Spread 26–75; Smoke-Developed 0–450
  iii. Class C: Flame Spread 76–200; Smoke-Developed 0–450

  Based on the results of the test, Flame Spread Index = 155 and Smoke Developed Index = 300, the PCM used in this study is classified as Class C and meets the building code for safe interior finish materials.

- Appendix C lists the “PCM Longevity Cycle Test” to show that the material will not deteriorate over time from daily or seasonal temperature cycling. According to the test results, fire retardant additives in the material will last for 15–22 years without measurable degradation in performance.

7. CONCLUSION

Although this investigation was not exhaustive, the findings indicate that PCM-type products may enable energy savings, peak shifting and temperature leveling for many installations.

The study simulated a typical office space (10 ft × 14 ft × 9 ft) subjected to a net heat load of 1365 BTU/hr, i.e., 1.08 BTU/hr/ft^3, without PCM and with PCM installed at both 0.56-lb/ft^2 and 2.0-lb/ft^2 (material weight per unit wall area) installation densities. As shown in Figure 34, the 2.0-lb/ft^2 PCM causes a delay in temperature rise above the comfort level temperature of 74 °F for up to 3 hours, which indicates that this PCM provides an effective means of peak shifting the cooling load.

The energy absorbed/released per ft^2 of wall is 48 BTU for the 0.56-lb/ft^2 density, and 172 BTU for the 2.0-lb/ft^2 density at 2–3 °F beyond the PCM melting temperature. These values can be used in design calculations to determine the amount of PCM required. Tools were developed to aid in proper design (see the Excel spread sheet and the expert model design).

Our recommendation is that architects and engineers consider the installation of PCM as a potential energy savings project for future Air Force remodeling projects or new construction. The installed cost of PCM should be evaluated versus local utility rates and local climate conditions to perform a business case evaluation to determine if PCM makes sense in a given project. To facilitate this evaluation, AFRL has prepared an Excel spreadsheet tool to help decision makers determine if a given PCM is right for their specific project.

As a further note, the variability in the results for the 100-W tests was significant; however this condition is not considered relevant, because this is an atypically small loading in an occupied structure.

8. REFERENCES

1. Sharma S.D., and Sagara K., "Latent Heat Storage Materials and Systems: A Review," International Journal of Green Energy 2 (2005) 1–56.

2. Khudhair A.M., and Farid M.M., "A review on energy conservation in building applications with thermal storage by latent heat using phase change materials," Energy Conversion and Management 45 (2004) 263–275.

3. Voelker C., Kornadt O., and Ostry M., "Temperature reduction due to the application of phase change materials," Energy and Buildings 40 (2008) 937–944.

4. Ahmad M., Bontemps A., Sallée H., and Quenard D., "Experimental investigation and computer simulation of thermal behavior of wallboards containing a phase change material," Energy and Buildings 38 (2006) 357–366.

5. Ahmad M., Bontemps A., Sallée H., and Quenard D., "Thermal testing and numerical simulation of a prototype cell using light wallboards coupling vacuum isolation panels and phase change material," Energy and Buildings 38 (2006) 673–681.

6. Kissock K.J., Hannig M.J., Whitney T.I., and Drake M.L., "Early results from testing phase change wallboard, IEA Annex 10, Phase Change Materials and Chemical Reactions for Thermal Energy Storage First Workshop," 16–17 April 1998, Adana, Turkey.

7. Kuznik F., Virgone J.h, Roux J.-J., "Energetic efficiency of room wall containing PCM wallboard: A full-scale experimental investigation," Energy and Buildings 40 (2008) 148–156.

8. Neeper D.A., "Thermal Dynamics of Wallboard with Latent Heat Storage," Solar Energy 68(5) (2000) 393–403.

9. Darkwa K., O'Callaghan P.W., "Simulation of phase change drywalls in a passive solar building," Applied Thermal Engineering 26 (2006) 853–858.

10. Koschenz M., Lehmann B., "Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings," Energy and Buildings 36 (2004) 567–578.

11. Pasupathy A., Athanasius L., Velraj R., and Seeniraj R.V., "Experimental investigation and numerical simulation analysis on the thermal performance of a building roof incorporating phase change material (PCM) for thermal management," Applied Thermal Engineering 28 (2008) 556–565.

12. Nagano K., Takeda S., Mochida T., Shimakura K., and Nakamura T., "Study of a floor supply air conditioning system using granular phase change material to augment building

mass thermal storage—Heat response in small scale experiments," Energy and Buildings 38 (2006) 436–446.

13. Darkwa J., "Mathematical evaluation of a buried phase change concrete cooling system for buildings," Applied Energy 86 (2009) 706–711.

14. Zhang Y., Zhou G, Lin K., Zhang Q., and Di H., "Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook," Building and Environment 42 (2007) 2197–2209.

15. Kosny J., Yarbrough D., Miller W., Petrie T., Childs P., and Syed A.M., "PCM-Enhanced Building Envelopes in Current ORNL Research Projects," Oak Ridge National Laboratory, 2006.

16. Muruganantham K., Phelan P., Horwath P., Ludlam D., and McDonald T., "Experimental Investigation of a Bio-Based Phase Change Material to Improve Building Energy Performance," Proceedings of ASME 2010 4th International Conference on Energy Sustainability , ES2010-90035, May 17-22, 2010 Phoenix, Arizona, USA.

17. Ismail K. A. R., and Castro J. N. C., "PCM Thermal Insulation in Buildings," International Journal of Energy Research, 21 (1997) 1281-1296.

18. Halford C.K., and Boehm R.F., "Modeling of phase change material peak load shifting," Energy and Buildings 39 (2007) 298–305.

19. Halford C.K., and Boehm R.F., "Modeling of phase change material peak load shifting," Proceedings of ISEC2005: 2005 International Solar Energy Conference, August 6–12, 2005, Orlando, Florida, ISEC2005-76035.

20. Hu H., and Argyropoulosz S.A., "Mathematical modeling of solidification and melting: a review," Modelling and Simulation in Materials Science and Engineering, 4 (1996) 371–396.

21. Verma P., Varun, Singal S.K., "Review of mathematical modeling on latent heat thermal energy storage systems using phase-change material," Renewable and Sustainable Energy Reviews 12 (2008) 999–1031.

22. Rabin Y., Korin E., "An efficient numerical solution for the multidimensional solidification (or melting) problem using a microcomputer," International Journal of Heat Mass Transfer, 36(3) (1993) 673–683.

23. Ibanez M., Lazaro A., Zalba B., and Cabeza L.F., "An approach to the simulation of PCM in building applications using TRNSYS," Applied Thermal Engineering 25 (2005) 1796–1807.

24. Heim D., and Clarke J.A., “Numerical modeling and thermal simulation of PCM–gypsum composites with ESP-r,” Energy and Buildings 36 (2004) 795–805.

25. Kuznik F., Virgone J., Roux J.-J., and Noel J., “Optimization of a phase change material wallboard for building use,” Applied Thermal Engineering 28 (2008) 1291–1298.

26. Kendrick C., and Walliman N., “Removing Unwanted Heat in Lightweight Buildings Using Phase Change Materials in Building Components: Simulation Modeling for PCM Plasterboard,” Architectural Science Review, 50(3) (2007) 265–273.

Appendix A: Excel Based Calculation Tool

Data Offered by the User: (**Data in red is provided by user**)

Amount of PCM needed for free cooling, and Payback Analysis of PCM usage in (name of building) FOR	1000	HOURS/YEAR	
Air Condition Load in Tons of Refrigeration.	932	Tons	
Total Floor Area of the building in Sq ft.	200000	Sq.ft	
Comfort Level	73	°F	(23 °C)
Phase Change Material (PCM) to start Melting at	71	°F	(20 °C)
No. of people is	1800		

Temperature is 19°C for at least 4hr/night for hundred nights in a year

Fan use is permitted

>>> Weather information in Locality ***

Month	Mean Temperature °F(°C) Daily Minimum	Daily Maximum	Remarks
Jan	59.2(15.1)	80.6(27)	71-73°F can be maintained all the time
Feb	61.9(16.6)	85.3(29.6)	71-73°F can be maintained all the time
Mar	66.6(19.2)	90.3(32.4)	71-73°Fcan be maintained for a few hours
Apr	70.7(21.5)	92.5(33.6)	PCm will not work this month
May	70.2(21.2)	90.9(32.7)	PCm will not work this month
Jun	67.8(19.9)	84.6(29.2)	PCm will not work this month
Jul	67.1(19.5)	81.5(27.5)	71-73°F can be maintained for a few hours
Aug	66.9(19.4)	81.3(27.4)	71-73°Fcan be maintained for a few hours
Sep	66.7(19.3)	82.4(28)	71-73°F can be maintained for a few hours
Oct	66.4(19.1)	81.9(27.7)	71-73°F can be maintained for a few hours
Nov	63(17.2)	79.9(26.6)	71-73°F can be maintained all the time
Dec	60.1(15.6)	78.6(25.9)	71-73°F can be maintained all the time

*** The above details are the mean maximum and minimum temperatures in Locality

**** available from World Weather Service.

>> Analysis from available weather info:

From the above information, it appears that for more than 100 days, PCM Melting at 71°F(20°C) is workable for free cooling.

(Based on the 4 months marked in green back-ground, and 5 months marked in yellow back-ground)

So, PCM Melting at 71 °F(20°C) will easily give comfortable temperature during day time for 100 days/year.

Number of days in a year of free cooling 100 Days

>>>> Calculation of Quantity of PCM Required, and Payback Period

					(IP Units)	
Air Conditioning Load is		932	Tons ref.		932	Tons ref.
1ton ref. = 3.52kW		3281	KW		11194003	btu/hr
No. of hours per day of free cooling		10	hours		10	hr
At these hours per day of Cooling or heating cycle it means		118103040	KJ/day		1.12E+08	btu/day
Latent heat of chosen PCM		220	KJ/Kg		94.6	btu/lb
Amount of PCM required for the free cooling will be		536832	Kg of PCM		1183298	lb of PCM
Price of PCM per Kg		6.00	$		3	$/lb
PCM cost (Bulk Price for the Grade)		**3220992**	**$**		**3549895**	$
Installation cost on site per Kg (1)		5.00	$		2.5	$
Cost of Labor		2684160	$** Tentative		2958246	$** Tentative
	Total Cost	**5905152**	**$** Tentative**		**6508141**	**$** Tentative**
Price of electricity per KWH		0.15	$		0.000044	$/BTU
Electricity Charges of AC usage (2)		492	$ Per Hour		493	$ Per Hour
If the system is usable for 1000 hours a year, then cost of Energy Saved		492096	$ Per Year		492536	$ Per Year
Assume saving on maintenance and depreciation of AC sys as a percentage of the energy saving above (3)		50	%		50	%
Cost of Saving on Maintenance & Depreciation of AC System		246048	$ Per Year		246268	$ Per Year
	Total saving	**738144**	**$ Per Year**		**738804**	**$ Per Year**
Pay Back Period if you count only cost of PCM		4.36	Years		4.80	Years
Pay Back Period if you count cost of PCM and Cost of Installation		8.00	Years		8.81	Years

(1)To Check & Alter the Cost of installation

(2) To Check & Alter the Cost of Electricity

(3) To Check and Correct the Cost of Depreciation & Maintenance of AC

Appendix B: Material Safety Data Sheet for Bio-PCM

BioPCM Material Safety Data Sheet

Product Name: BioPCM Phase Change Material- 23B
Date Issued: July 2, 2008
MATERIAL SAFTEY DATA SHEET
July 2, 2008

PHASE CHANGE COMPONENT OF BIOPCM- 23C/73C

SECTION 1. IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY

Product identification
Synonyms/Trade Names: Derivatives of Fatty Acids, Thermester 23B
Product uses
Common uses for this product are thermal energy storage,
Company
Phase Change Energy Solutions
120 East Pritchard Street
Asheboro, NC 27203
336-629-3000

SECTION 2. COMPOSITION/INFORMATION ON INGREDIENTS

Substance/Preparation(mixture):
Fatty Acid Derivative Mixture 67254-79-9, 68937-84-8, 126950-60-5, 85681-70-5

SECTION 3. HAZARDS IDENTIFICATION

European Hazard Classification: This product is not classified as dangerous according to Directive 67/548/EEC.
Emergency Overview: North America - Non - Hazardous
Potential Health Effects:
Eye - Accidental exposure to the eyes may produce a mild but transient irritation.
Skin - Very mild to no irritation expected.
Inhalation - No harmful effects expected with normal use.
Ingestion - May cause gastrointestinal irritation.
If product is heated, vaporization can occur. Eye, skin, and upper respiratory irritation can occur.
Physical/Chemical Hazards: None identified.
Environmental Hazards: None identified.

SECTION 4. FIRST AID MEASURES

Eye - In case of contact, immediately flush eyes with plenty of water for at least 15 minutes. Get medical attention.
Skin - Wash skin with soap and water upon contact. Remove contaminated clothing. If irritation persists, get medical attention. Wash clothing before reuse.
Inhalation - Remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical attention immediately.
Ingestion - If swallowed, do NOT induce vomiting. Get medical attention. Never give anything by mouth to an unconscious person.

SECTION 5. FIRE FIGHTING MEASURES

Extinguishing media: SMALL FIRES: CO 2 or dry chemical
LARGE FIRES: Foam
Unsuitable extinguishing media: Water spray may be ineffective on fire.
Explosive limits in air:
Upper: Not available
Lower: Not available
Special Protective Equipment: Wear self-contained breathing apparatus and full protective clothing.
Other Fire Fighting Considerations: Cool containers with flooding quantities of water until well after fire is out.

SECTION 6. ACCIDENTAL RELEASE MEASURES

Personal Precautions: Wear protective clothing and equipment. An appropriate NIOSH/MSHA approved respirator should be used if a mist or vapor is generated.
Environmental Precautions: Dike flow of spilled material using soil or sandbags to minimize contamination of drains, surface and ground waters.
Procedures for Spill/Leak Clean-up: Ventilate area and eliminate all ignition sources. Contain spill. Absorb or cover with dry earth, sand or other non-combustible material and transfer
to containers for disposal.

SECTION 7. HANDLING AND STORAGE

Handling: Handle in accordance with good hygiene and safety procedures. Avoid contact with eyes, skin, and clothing. Wash thoroughly after handling. When transferring materials ground and bond containers, use spark proof tools and explosion proof equipment. Since empty containers contain product residue, follow all hazard warnings and precautions even after container is emptied. Keep away from sources of ignition.
Storage: Can be stored in most common storage vessels including carbon steel, aluminum, fiberglass, and stainless steel. Keep away from heat, sparks or open flames. Keep away from possible contact with incompatible substances. Store in a cool dry place in accordance with NFPA 30.

SECTION 8. EXPOSURE CONTROLS/PERSONAL PROTECTION

General Precautions: Good industrial hygiene should be followed. Avoid breathing (heated) vapors. Avoid eye and skin contact.
Exposure Limit Values: Not established.
Exposure Controls:
Engineering Controls: Ventilation: Local exhaust - preferred
Mechanical - may be necessary if working at elevated temperatures or in enclosed areas.
Personal Protective Equipment:
Eye - Goggles or face shield with goggles, dependent upon potential exposure
Skin - Protective gloves: Nitrile
Dependent upon degree of potential exposure, additional personal protectiveequipment may be required, such as chemical boots and full protective clothing.
Inhalation - None required for ambient temperature, although an appropriate NIOSH/MSHA approved air-purifying respirator should be used if a mist or vapor is generated. A NIOSH/MSHA approved self-contained breathing apparatus or air-supplied respirator is recommended if the concentration exceeds the capacity of cartridge respirator.
Other Controls: Boots, eye wash fountain, safety shower, apron, protective clothing.

SECTION 9. PHYSICAL AND CHEMICAL PROPERTIES

General Information:
Physical State at 25 _C: Liquid
Density: 0.83
Appearance: Clear
Odor: Musty
Important health, safety and environmental information:
pH: Not applicable
Flammability (solid, gas): Not available
Boiling point: >480∞ F (248.9∞ C)
Explosive properties: Not available
Oxidising properties: Not available
Solubility:
Water solubility: Negligible
Fat solubility (solvent-oil to be specified): Not available
Partition coefficient: n-octanol/water: Not available
Viscosity: Not available
Vapor density: Not available
Evaporation Rate (nBuOAc=1): Not available
Explosive Limits: Not available
Auto ignition temperature: Not available
Coefficient of water/oil distribution: Not available

SECTION 10. STABILITY AND REACTIVITY

Stability: Stable under normal operational procedures.
Conditions to Avoid: Not available
Materials to Avoid: Avoid oxidizing agents
Hazardous Decomposition Products: Carbon monoxide with incomplete combustion.
Hazardous Polymerization: Will not occur.

SECTION 11. TOXICOLOGICAL

ACUTE ORAL TOXICITY/RATS
Practically non-toxic. The acute oral LD50 was greater than 5 g/kg body weight.
EYE IRRITATION/RABBITS
The application of undiluted material to the rabbit's eye produced no irritation.
SKIN IRRITATION/HUMANS
Mild irritation.

SECTION 12. ECOLOGICAL INFORMATION

Ecological Toxicity - Not Determined
Environmental Fate - Not Determined

SECTION 13. DISPOSAL CONSIDERATIONS

Dispose of in compliance with all Federal, State, and local regulations.

SECTION 14. TRANSPORT INFORMATION

Not classified in DOT, ADR/RID, IMDG, IATA/ICAO

SECTION 15. ADDITIONAL REGULATORY INFORMATION

TSCA Inventory Status - This product and/or all of its components are included on the TSCA Inventory of Chemical Substances.
TSCA 12(B) Components - None
SARA 311/312 Hazardous Categories - None
SARA 313 Toxic Chemicals - None

SECTION 16. OTHER INFORMATION

HMIS Ratings:
Health - 1
Flammability - 1
Reactivity - 0
NFPA Ratings
Health - none
Flammability - none
Reactivity - none

FIRE SUPPRESSION COMPONENT OF BIOPCM- 2C/73C

SECTION 1. CHEMICAL PRODUCT AND COMPANY IDENTIFICATION

Company Information:
Phase Change Energy Solutions, Inc.
120 E. Pritchard Street
Asheboro, NC 27203

Telephone Numbers:
Phone: 336-629-3000
FAX: 336-629-3100

SECTION 2. COMPOSITION AND INFORMATION ON INGREDIENTS

Composition: This product is a proprietary blend. Information will be provided to a physician as needed.

SECTION 3. TOXICOLOGICAL INFORMATION

This product is ph neutral and contains no toxic components.
No SARA 313 reportable component exists in this product.
No reportable component exists under RCRA 40 CFR part 261 & 262.

SECTION 4. HAZARD IDENTIFICATION

Eye Contact: May cause redness, burning, and irritation.

Skin Contact: Other than dryness of skin, no adverse effects are expected from brief contact.

Inhalation: If vapors or mist from heating cause discomfort in nose and throat, move to fresh air.

Ingestion: May cause stomach discomfort, nausea, and diarrhea.

Chronic: None known

Medical Conditions Aggravated by Exposure: There is no evidence this product aggravates any existing medical conditions.

SECTION 5. FIRST AID MEASURES

Eyes: Immediately flush eyes with large amounts of water for at least 15 minutes. Get medical attention if needed. Do not attempt to neutralize with chemical agents.

Skin: Wash skin with plenty of soap and water for several minutes. Get medical attention if skin irritation develops or persists.

Ingestion: If patient is conscious and can swallow, give two glasses of water (16oz). Induce vomiting as directed by medical personnel. Do not induce vomiting or give anything by mouth to an unconscious or convulsing person.

Inhalation: Use proper respiratory protection based on type of fire.

SECTION 6. EXPOSURE CONTROL/ PERSONAL PROTECTION

Eye and Face Protection: Avoid eye contact; chemical type goggles with face shield can be worn to protect eyes and face.

Skin Protection: Workers should wash exposed skin several times with soap and water. Soiled work clothing should be laundered or dry cleaned.

Inhalation: Use proper respiratory protection if needed.

Exposure Limit for the Total Product: None established for product.

SECTION 7. ECOLOGICAL INFORMATION/ ACCIDENTAL RELEASE MEASURES

No adverse impact on the environment. Dispose of in accordance with Federal, State, and Local regulations. Always consult local EPA for disposal regulations. Never dispose into sewers or water ways without contacting the local EPA for approval.

Spill will result in slippery surface conditions.

SECTION 8. STABILITY AND REACTIVITY

Hazardous Polymerizations: Do not occur.
Chemical Stability: Stable
Conditions to Avoid: Strong oxidizing agents
Hazardous Decomposition Products: None known

SECTION 9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance: Red in color

Odor: Mild pleasant clean smell

Boiling point: 270° F

PH: 7.3 +/- 0.2

Melting/ freezing Point: Not determined

Evaporation Rate: Same as water

Specific Gravity: (water=1) 1.041

SECTION 10. FIRE FIGHTING MEASURES

Flashpoint: Not Determined

Flammable Limits: Not Determined

This product is a fire extinguishing product

SECTION 11. HANDLING AND STORAGE

Handling: Minimum feasible handling temperatures should be maintained between 33°- 125° F. Keep container closed; keep eye wash available, water based keep away from electrical exposed wires or electrical fires.

SECTION 12. TRANSPORT INFORMATION

Under DOT code 55 for shipping

SECTION 13. OTHER INFORMATION

The information on this MSDS was obtained from sources which we believe are reliable. However the information is provided without any warranty, expressed or implied, regarding its correctness. Some information presented and conclusions herein are from sources other than test data on the substance itself. We do not assume responsibility and expressly disclaim liability for loss, damage or expense arising out of or in any way connected with handling, storage, use or disposal of the product.

Appendix C: Report for Testing Surface Burning Characteristics of PCM According to ASTM E-84

Intertek

ASTM E-84
TEST FOR SURFACE BURNING
CHARACTERISTICS OF
BUILDING MATERIALS

"Biopcm 23 (Thermo Mat)"

Report No. 3188045SAT-001A

**** MODIFIED***

August 25, 2009

Prepared For:

Vesture Corporation
120 East Pritchard Street
Asheboro, NC 27203

Intertek Testing Services NA, Inc.
16015 Shady Falls Road, Elmendorf, TX 78112
Telephone: 1-800-966-5253 Fax: 1-210-635-8101
Web: www.intertek-etlsemko.com

ABSTRACT

Test Material:	"Biopcm 23 (Thermo Mat)"
Test Standard:	**ASTM E - 84 TEST FOR SURFACE BURNING CHARACTERISTICS OF BUILDING MATERIALS (UL 723, UBC 8-1, NFPA 255)**
Test Date:	August 19, 2009
Test Sponsor:	Vesture/PCES
Test Results:	**FLAME SPREAD INDEX** 155 **SMOKE DEVELOPED INDEX** 300

Philip So
Tunnel Operator

Date: August 25, 2009

Reviewed and approved:

Miguel Zamarripa
Project Manager

Date: August 25, 2009

Intertek

I. INTRODUCTION

This report describes the results of the ASTM E-84 TEST FOR SURFACE BURNING CHARACTERISTICS OF BUILDING MATERIALS a method for determining the comparative surface burning behavior of building materials. This test is applicable to exposed surfaces, such as ceilings or walls, provided that the material or assembly of materials, by its own structural quality or the manner in which it is tested and intended for use, is capable of supporting itself in position or being supported during the test period.

The purpose of the method is to determine the relative burning behavior of the material by observing the flame spread along the specimen. Flame spread and smoke density developed are reported, however, there is not necessarily a relationship between these two measurements.

"The use of supporting materials on the underside of the test specimen may lower the flame spread index from that which might be obtained if the specimen could be tested without such support... This method may not be appropriate for obtaining comparative surface burning behavior of some cellular plastic materials... Testing of materials that melt, drip, or delaminate to such a degree that the continuity of the flame front is destroyed, results in low flame spread indices that do not relate directly to indices obtained by testing materials that remain in place."

This test method is also published under the following designations:

NFPA 255
UL 723
UBC 8-1

This standard should be used to measure and describe the properties of materials, products, or assemblies in response to heat and flame under controlled laboratory conditions and should not be used to describe or appraise the fire hazard or fire risk of materials, products, or assemblies under actual fire conditions. However, results of this test may be used as elements of a fire risk assessment which takes into account all of the factors which are pertinent to an assessment of the fire hazard of a particular end use.

II. PURPOSE

The ASTM E-84 (25 foot tunnel) test method is intended to compare the surface flame spread and smoke developed measurements to those obtained from tests of mineral fiber cement board and select grade red oak flooring. The test specimen surface (18 inches wide and 24 feet long) is exposed to a flaming fire exposure during the 10 minute test duration, while flame spread over its surface and density of the resulting smoke are measured and recorded. Test results are presented as the computed comparisons to the standard calibration materials.

The furnace is considered under calibration when a 10 minute test of red oak decking will pass flame out the end of the tunnel in five minutes, 30 seconds, plus or minus 15 seconds. Mineral fiber cement board forms the zero point for both flame spread and smoke developed indexes, while the red oak flooring smoke developed index is set as 100.

III. DESCRIPTION OF TEST SPECIMENS

Specimen Identification:	"Biopcm 23 (Thermo Mat)"
Date Received:	8/15/2009
Date Prepared:	8/19/2007
Conditioning (73°F & 50% R.H.):	4
Specimen Width (in):	16
Specimen Length (ft):	24
Specimen Thickness:	0.4000
Material Weight:	N/A
Total Specimen Weight:	24
Adhesive or coating application rate:	N/A

Mounting Method:

The specimen was supported by rods and wire.

Specimen Description:

The specimen was described by the client as the "Biopcm 23 (Thermo Mat)". The specimen consisted of (1) 24-ft. long x 16-in. wide x 0.4000-in. thick, white plastic material with pink liquid pockets. The product was received by our personnel in good condition. The specimen was identified by the client as "BIOPCM 23 (THERMO MAT), 900.01.2305616."

This was a modified test because specimen did not meet width requirements as stated by the ASTM-E84 Test Standard.

This test was witness by Mr. Peter Horwath from Vesture/PCES on 08/19/09.

Intertek

IV. TEST RESULTS & OBSERVATIONS

The test results, computed on the basis of observed flame front advance and electronic smoke density measurements are presented in the following table.

While no longer a part of this standard test method, the Fuel Contributed Value has been computed, and may be found on the computer printout sheet in the Appendix.

Test Specimen	Flame Spread Index	Smoke Developed Index
Mineral Fiber Cement Board	0	0
Red Oak Flooring		100
"Biopcm 23 (Thermo Mat)"	155	300

The data sheets are included in Appendix A. These sheets are actual print-outs of the computerized data system which monitors the tunnel furnace, and contain all calibration and specimen data needed to calculate the test results.

V. OBSERVATIONS

During the test, the specimen was observed to behave in the following manner: The specimen began to melt at 0:05 (min:sec). The specimen ignited at 0:10 (min:sec). Flaming drops were observed at 0:14 (min:sec) and the floor of the apparatus ignited at 0:15 (min:sec). Flames reached the end of the tunnel at 2:59 (min:sec). The test continued for the 10:00 duration. After the conclusion of test, a 60-second after flame was observed.

After the test, the specimen was observed to be damaged as follows: The specimen was consumed from 0-ft. – 24-ft.

Intertek

APPENDIX

ASTM E-84
DATA SHEETS

Intertek

ASTM E84-09

Client: VESTURE/PCES

Date: 08/19/09

Project Number: 3188045SAT-001A

Test Number: 1

Operator: PS/AM

Specimen ID:
"BIOPCM 23 (THERMO MAT), 900.01.2305616. "THE SPECIMEN WAS SUPPORTED BY RODS AND WIRE. THE TEST WAS WITNESSED BY PETER HORWATH FROM VESTURE/PCES.

TEST RESULTS

FLAME SPREAD INDEX: 155

SMOKE DEVELOPED INDEX: 300

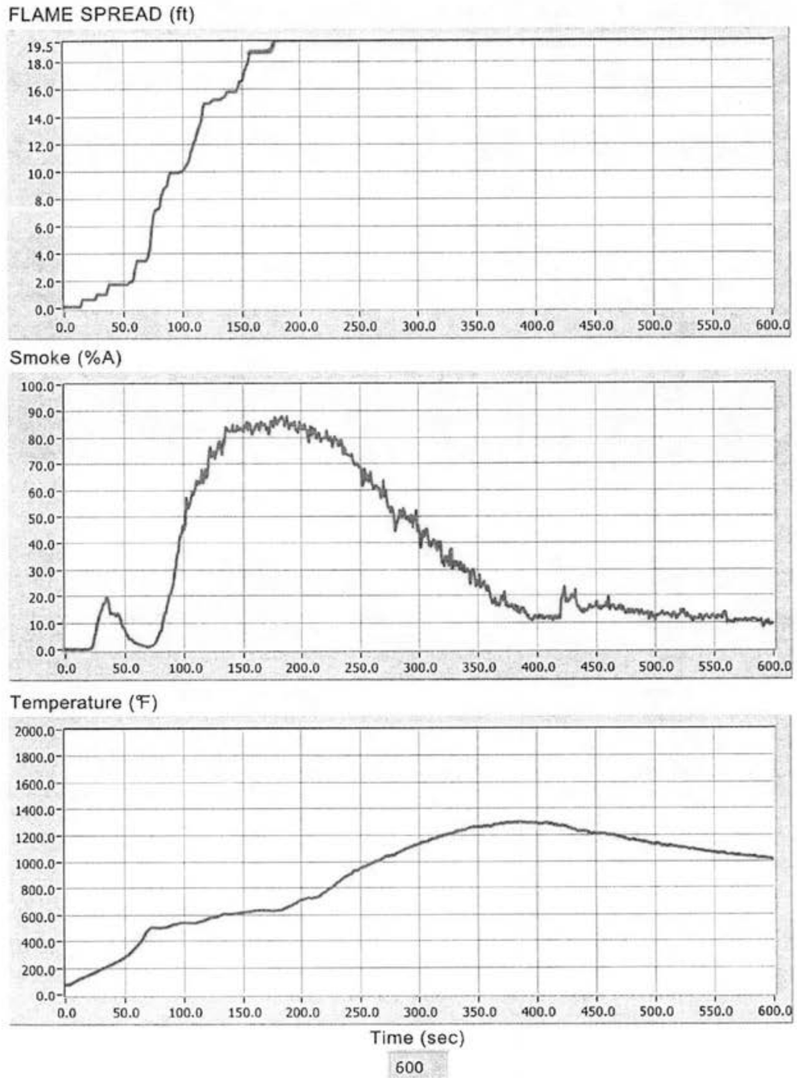
SPECIMEN DATA . . .

Time to ignition (sec):	10
Time to Max FS (sec):	179
Maximum FS (feet):	19.5
Time to 980 °F (sec):	259
Time to End of Tunnel (sec):	179
Max Temperature (F):	1300
Time to Max Temperature (sec):	385
Total Fuel Burned (cubic feet):	52.47
FS* Time Area (ft*min):	163.3
Smoke Area (%A*min):	342.9
Unrounded FSI:	154.7

CALIBRATION DATA . . .

Time to ignition of last Red Oak (sec):	36.0
Red Oak Smoke Area (%A*min):	109.8

Project No: 3188045SAT-001A

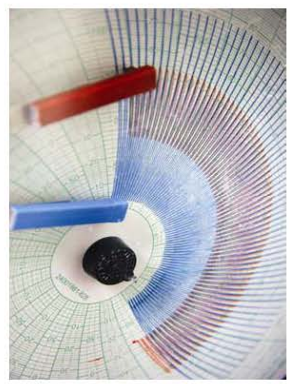


Appendix D: PCM Longevity Cycle Testing

BioPCM™ Longevity Cycle Testing

Peter Horwath 11-03-08
Phase Change Energy Solutions, Inc.

Many phase change materials particularly the inorganic varieties are prone to deterioration over time. As the materials go through freeze-thaw cycles the materials break down gradually reducing the amount of latent heat storage per transition. Organic phase change materials such as Phase Change Energy Solutions, Inc.'s BioPCM™ have been shown to be very resistant to this deterioration. To insure the reliability of BioPCM™ however, and to address any concerns related to compatibility with adjacent materials, Phase Change Energy Solutions, Inc. has an ongoing longevity research program in place. Below are results to date on several experiments being conducted at our Asheboro NC location.



Test Setup:

Longevity cycle testing was preformed in a Standard Environmental Systems Model 10C Environmental chamber equipped with a Honeywell DR4200 Paper charter. This chamber is programmed to perform the following cycle:

Action	Duration
Begin at 20C	
Ramp to -20C	5 minutes
Hold -20C	20 minutes
Ramp to 60C	10 minutes
Hold 60C	20 minutes
Ramp to 20C	5 minutes

The above defined cycle allows for one full solid to liquid cycle for our samples each hour. We are using 270 cycles to represent one year's worth of cycles in the field. This is inline with DOE U.S. Department of Energy standards.

Periodically, a number of samples were taken of different samples from the environmental chamber and sent for analysis by Dr. Russell Sutterlin of the University of Alabama Chemistry Department

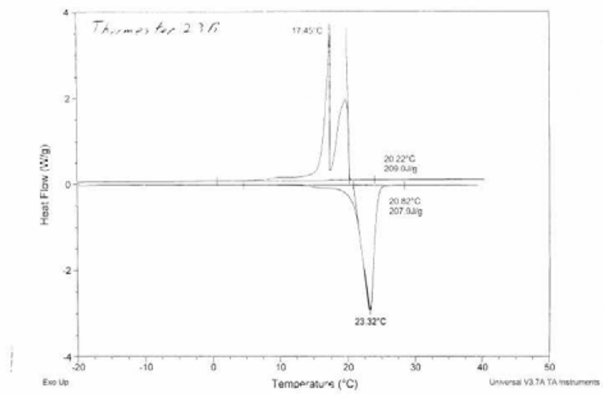
Observations:

Attached are five thermal performance graphs generated by Dr. Russell Sutterlin of the University of Alabama Chemistry Department via a DSC (Differential Scanning Calorimeter)

CONTROL SAMPLE

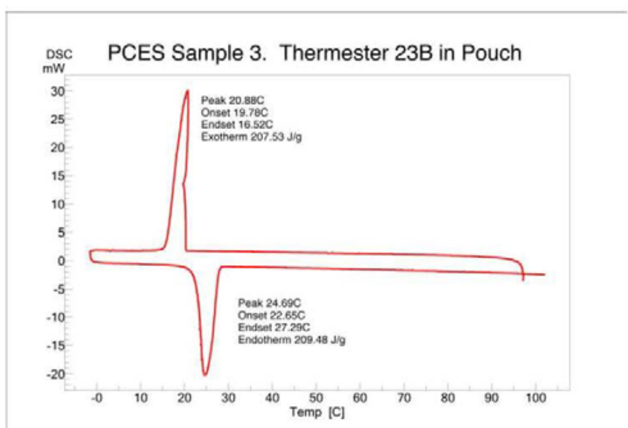
BioPCM™ 23 deg Celsius 0 Cycles

Control sample preformed shortly after manufacture.



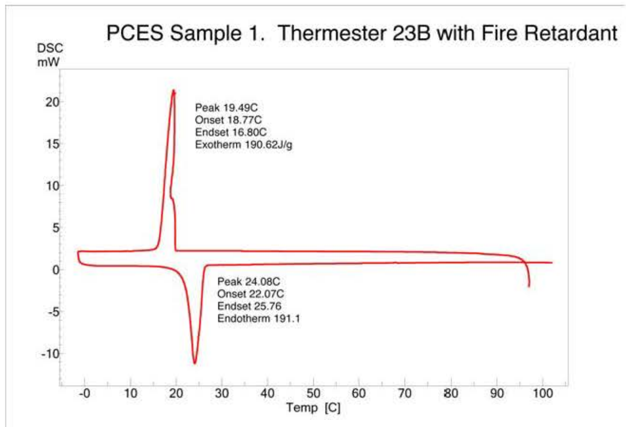
BioPCM™ 23 deg Celsius 5953 Cycles 22 years

Sample was enclosed within PCES proprietary multilayer polyfilm throughout duration of cycle tests to determine whether the polyfilm would interact with the BioPCM™ Sample shows little to no breakdown over duration of test



BioPCM™ 23 deg Celsius with Fire Suppressant 4017 Cycles 15 yrs

Sample was a blend of BioPCM™ and Fire Suppressant. Mixture was emulsified prior to start of cycle testing. Sample shows little to no breakdown over duration of test. Reduction of latent heat storage capacity is due to the ratio of net BioPCM™ volume vs. gross volume of sample.



LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

A	area (m^2)
AFCESA	HQ Air Force Civil Engineer Support Agency
AFRL	Air Force Research Laboratory
BTU	British thermal unit
C_p	material specific heat (kJ/kg K)
CFM	cubic feet per minute (ft^3/min)
HVAC	heating, ventilation, and air conditioning
K	thermal conductivity (W/m K)
L	PCM latent heat (kJ/kg)
LHTES	latent heat thermal energy storage
PCM	phase change materials
q"	heat flux (W/m^2)
R	thermal resistance (m^2K/ W)
t	time
T	temperature (K)
ΔT	temperature difference (K)
U	overall thermal conductivity coefficient (W/m^2 K)
VIP	vacuum insulation panel
W	watts

Subscripts

i	index number identifying items 1, 2, …*n* in a series
l	liquid
m	melting
s	solid
x	*x*-direction
y	*y*-direction
z	*z*-direction